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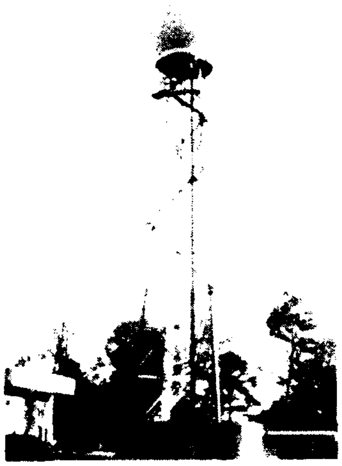

MISCELLANEOUS PAPER EL-79-6

MILITARY HYDROLOGY

Report 18

STATE-OF-THE-ART REVIEW AND ANNOTATED BIBLIOGRAPHY OF RADAR-RAIN GAGE RELATIONS AND SHORT-TERM WEATHER FORECASTING

by

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April 1991
Report 18 of a Series

Approved for Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Contract No. DAGG29-81-D-0100, Delivery Order 2113
US Army Summer Faculty Research and Engineering Program
Scientific Services Program

Monitored by Environmental Laboratory
US Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1991	Report 18 of a series

4. TITLE AND SUBTITLE
Military Hydrology; Report 18, State-of-the-Art Review and Annotated Bibliography of Radar-Rain Gage Relations and Short-term Weather Forecasting

5. FUNDING NUMBERS
Contract No.
DAGG29-81-D-0100
Delivery Order 2113
Project No. 4A762719AT40
Task Area BO

6. AUTHOR(S)
McDaniel, Willard R.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
East Texas State University, Commerce, TX 75428

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAEWES, Environmental Laboratory
3909 Halls Ferry Road, Vicksburg, MS 39180-6199
US Army Corps of Engineers, Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Miscellaneous Paper EL-79-6

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report provides a general overview of the current state of the art of radar-rain gage relations and short-term weather forecasting. The review highlights the problems inherent in attempting to determine total precipitation entirely from radar data. An annotated bibliography is included.

14. SUBJECT TERMS
Military hydrology
Radar rainfall
Weather forecasting
Weather radar

15. NUMBER OF PAGES
109

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

PREFACE

The work documented in this report was performed by Dr. Willard R. McDaniel, Professor of Physics, Department of Physics, East Texas State University, Commerce, TX. At the time, Dr. McDaniel was with the US Army Summer Faculty Research and Engineering Program working under contract No. DAGG29-81-D-011, Delivery Order 2113. The effort was funded by Headquarters, US Army Corps of Engineers (HQUSACE) under Department of the Army Project No. 4A762719AT40, "Mobility, Soils and Weapons Effects Technology," Task Area BO, Work Unit 042, "Tactical Hydrology." LTC Ted C. Scott was the HQUSACE Technical Monitor.

Principal Investigators of Work Unit 042 are Messrs. John G. Collins and Thomas L. Engdahl, Environmental Constraints Group (ECG), Environmental Systems Division (ESD), Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES). The work unit was conducted under the general supervision of Mr. Malcolm P. Keown, Chief, ECG; Dr. Victor E. LaGarde, Chief, ESD; and Dr. John Harrison, Chief, EL. This report was edited by Ms. Janean C. Shirley of the WES Information Technology Laboratory.

COL Larry B. Fulton, EN, was the Commander and Director of WES. Dr. Robert W. Whalin was the Technical Director.

This report should be cited as follows:

> McDaniel, Willard R. 1991. "Military Hydrology; Report 18, State-of-the-Art Review and Annotated Bibliography of Radar-Rain Gage Relations and Short-term Weather Forecasting," Miscellaneous Paper EL-79-6, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
inches	2.54	centimetres
miles (US nautical)	1.852	kilometres
miles (US statute)	1.609347	kilometres
millibars	100.0	pascals
square miles (US nautical)	2.589988	square kilometres

MILITARY HYDROLOGY
STATE-OF-THE-ART REVIEW AND ANNOTATED BIBLIOGRAPHY OF RADAR-RAIN GAGE RELATIONS AND SHORT-TERM WEATHER FORECASTING

PART I: INTRODUCTION

Background

1. Under the Meteorological/Environmental Plan for Action, Phase II, approved for implementation on 26 January 1983, the US Army Corps of Engineers (USACE) has been tasked to implement a Research, Development Testing, and Evaluation program that will (a) provide the Army with environmental effects information needed to operate in a realistic battlefield environment, and (b) provide the Army with the capability for near real-time environmental effects assessment on military materiel and operations in combat. In response to this tasking, the Directorate of Research and Development, USACE, initiated the AirLand Battlefield Environment (ABLE) Thrust Program. This new initiative will develop the technologies to provide the field Army with the operational capability to perform and exploit battlefield effects assessments for tactical advantage.

2. Military hydrology, one facet of the ABLE Thrust Program, is a specialized field of study that deals with the effects of surface and subsurface water on planning and conducting military operations. In 1977, the Office, Chief of Engineers, approved a military hydrology research program; management responsibility was subsequently assigned to the Environmental Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

3. The objective of military hydrology research is to develop an improved hydrologic capability for the Armed Forces with emphasis on applications in the tactical environment. To meet this overall objective, research is being conducted in four areas: (a) weather-hydrology interactions, (b) state of the ground, (c) streamflow, and (d) water supply.

4. Previously published military hydrology reports are listed inside the back cover of this report. This report is the second contribution to the weather-hydrology interactions research study area. The study area is oriented primarily toward the development procedures to reduce the time required for obtaining and processing environmental data and for using these data in making hydrologic forecasts in tactical environments. Although emphasis is to be initially focused on the remote acquisition and subsequent processing of weather information, a comparable effort will be placed on terrain information in future years.

Purpose and Scope

5. The purpose of this report is to provide a review of (a) calibration techniques for radar rainfall totals with rain gages, and (b) state-of-the-art models for real-time

precipitation analysis and forecasting. Military Hydrology Report 8, "Feasibility of Utilizing Satellite and Radar Data in Hydrologic Forecasting," outlines the role these tools may play in determining precipitation in an area. At this time, however, it is impossible to accurately determine total precipitation in a given area by radar alone. It is necessary to calibrate the radar with rain gages if reasonably accurate precipitation amounts are to be determined.

6. This report is divided into two major parts. Part I is a review of the relations between rain gages and weather radars. The various factors that necessitate radar calibration are investigated. An annotated bibliography with abstracts is given in Appendix A. Part II includes discussions on current and projected systems for real-time forecasts of precipitation. Appendix B contains an annotated bibliography on this subject.

PART II: RADAR-RAIN GAGE RELATIONS

7. For more than 40 years, an interest in measuring rainfall with radar has existed. The development of the technology has been delayed because of a lack of a unique relation between the backscattering of energy by raindrops and their volume. The backscattered radar power for precipitation particles is proportional to the summation of the sixth power of particle diameters (D_i^6) in a unit volume intersected by the radar beam, and the radar reflectivity factor Z measured in mm^6/m^3 is defined as

$$Z = \sum_c N_i D_i^6 = \int_0^\infty n(D) D^6 dD \tag{1}$$

where N_i is the number of drops per unit volume of air with a diameter D_i and $N(D)$ is the number of drops with diameters between D and $D+dD$ in a unit volume of air.

8. The rainfall rate R is related to D through the following equation assuming vertical air motions are absent.

$$R = \frac{\Pi}{6} \int_0^\infty N(D) D^3 V_t(D) dD \tag{2}$$

where $V_t(D)$ is the terminal velocity of drop of diameter D that is approximated in cm/s units at $V_t = 1400D^{0.5}$ (Spilhaus 1948). By substituting the Marshall-Palmer exponential drop-size distribution (Marshall and Palmer 1948) into these equations and using the empirical relation between V_t and D, the expression between Z and R takes the form

$$Z = AR^b \tag{3}$$

9. It follows that if the drop-size distribution is exponential and known and if the vertical air motions are small relative to the drop terminal velocities, there is no fundamental limit to the accuracy of radar rainfall estimates. A problem arises because the drop-size spectrum is rarely known and varies both areally and temporally between storms and even within a single rain event. Further, it has been found that vertical velocities within a storm can be of the same magnitude as the terminal velocity of the drops. Thus the Z-R relation is not unique. Battan (1973) listed 69 Z-R relations. One of the most widely used expressions based on the empirical study of Marshall and Palmer (1948) is

$$Z = 200R^{1.6} \tag{4}$$

For the Next Generation Weather Radar (NEXRAD) Program, the proposed Z-R relation is

$$Z = 300R^{1.4} \tag{5}$$

(Ahnert et al. 1983). This is the same relation used by Woodley and Herndon (1970) and referred to as the Miami Z-R relation for the Florida Area Cumulus Experiment (FACE) Project.

10. Several possible sources account for value differences between the radar and the rain gages. These can be classified as a) errors in estimating radar reflectivity, b) variations in the Z-R relation, and c) gage and radar sampling differences.

11. Brandes and Wilson (1982) stated that system errors could result from incorrect hardware calibration. However, Harrold, English, and Nicholass (1974) believed that these errors are small relative to those caused by meteorological and geographical factors. A more serious problem can be caused by beam blockage near the radar site; trees, buildings, and hills can cause permanent radar obstructions. Bellon and Austin (1977) adjusted their data by developing a series of Constant Altitude Plan Position Indicator (CAPPI) maps which eliminated the ground effects.

12. Anomalous propagation caused by extreme gradients of temperature and humidity can lead to erroneous rainfall estimates. Temperature inversions with decreasing humidity aloft can lead to ducting (trapping) of the radar signal. This results in the return from targets at extended distances over large areas. Temperature inversions and humidity variations under heavy thunderstorm downdrafts may cause super-refraction of the radar signal. Areas of super-refraction will display a significant reduction in rainfall estimates.

13. Attenuation of the microwave signal by precipitation particles may be used to determine rainfall rates. Battan (1973) suggested that average rainfall rates could be determined by measuring signal attenuation, which is wavelength-dependent, with the shortest wavelengths having the greatest losses. Eccles (1978) had shown some success at figuring rainfall rates using dual wavelength radars and measuring differential attenuation. Seliga and Bringi (1976, 1978) proposed calculating rainfall from drop-size distribution parameters estimated from differential reflectivity between horizontally and vertically polarized waves. Ulbrich and Atlas (1975) also proposed using radar reflectivity and attenuation to determine the drop-size distribution which could then be converted to rainfall rate. Another source of attenuation error is the water film collected on the radome covering the radar antenna. Usually no attempt is made to correct for this factor because of the difficulty in determining the thickness of the moisture layer and the rate of evaporation.

14. Time and space averaging of radar measurements can lead to errors in estimating rainfall amounts. Radar data are ordinarily obtained by azimuth scanning at low elevation angles and making measurements at discrete angular and range intervals. The reflectivity value is converted to rainfall rate using the proper Z-R relations. Rates are

accumulated over time to give the spatial distribution of precipitation. This technique results in space and time sampling errors that relate to storm characteristics such as precipitation intensity and storm duration, size, and movement.

15. Additional errors can result from the spatial precipitation features smaller in size than twice the signal-averaging interval. Thus, small-scale events could escape detection by the radar but still be detected on the ground if located over a rain gage. At greater ranges the likelihood of partial beam filling and a difference between what the radar sees and what reaches the ground increases. Factors that influence a raindrop as it falls from the cloud include growth or evaporation, advection, and vertical air motion. Kinser and Gunn (1951) estimate evaporation losses of up to 15 percent using the Marshall-Palmer (1948) drop size distribution with a temperature of 20^{0} C and a relative humidity of 80 percent in a fall of 300 m. Harrold, English, and Nicholass (1974) estimate that the drift of rain below the cloud may be as much as 1-2 km and may produce a calibration error of 20 percent on days of strong winds and large rainfall gradients.

16. Stout and Mueller (1968) recognized the tremendous variation that can exist in the Z-R relation. Their work included a discussion of the effects of geographical differences, different rain types, stratification by synoptic type, stratification by thermodynamic instability, within-storm variations, and the influence of evaporation, coalescence, and accretion.

17. Variations in the Z-R relation can have a significant effect on the rainfall estimate. Martner (1975), Carbone and Nelson (1978), and others reported that the Z-R relation can vary with different phases of the thunderstorm cycle. Coefficient values in Equation 3 increase and the exponent decreases with increasing convective activity. Twomey (1953) stated that the large scatter in drop spectra over time periods of 5 to 10 min will preclude an accuracy greater than a factor of 2 in the Z-R relation. Table 1 lists physical mechanisms and their probable influence on the Z-R relation (Wilson and Brandes 1979).

18. At greater ranges, the radar beam intersects higher portions of the cloud. At these higher elevations, temperatures are frequently at or below freezing. Precipitation particles can be in some form other than liquid water. Both hail and melting snow have higher reflectivities (bright band values) than does liquid water. Therefore, erroneously high rainfall rate estimates can result, a problem particularly pronounced in stratiform clouds associated with frontal systems (Harrold, English, and Nicholass 1974).

19. Errors can be introduced into the system from rain gages. Larson (1971) and the World Meteorological Organization (1973) have published annotated bibliographies on rain gage catchments and their deficiencies. Sources of error include gage wetting, evaporation, tilt of the gage, splash into or out of the gage, and air flow around the orifice. Careful placement of the gage can hold errors from factors other than air flow to approximately 2 percent of expected catchment.

Table 1
Microphysical and Kinematic Influences on Z-R Relations and the Effect on Radar Rainfall Estimates When No Adjustment Is Applied

Process	Change in $Z = AR^b$ A	Change in $Z = AR^b$ b	Probable Effect on Radar Rainfall if Not Corrected	Possible Region of Maximum Influence
Microphysical				
Evaporation	Increase	Decrease	Overestimate	Inflow regions, fringe areas
Accretion of cloud particles	Decrease	Increase	Underestimate	Downdraft
Collision and coalescence	Increase	Decrease	Overestimate	Reflectivity core
Breakup	Decrease	Decrease	Underestimate	Reflectivity core
Kinematic				
Size sorting	Increase	Decrease	Overestimate	Region of strong inflow or outflow
Vertical motion				
Updraft	Increase	Decrease	Overestimate	
Downdraft	Decrease	Increase	Underestimate	

Source: Wilson and Brandes (1979).

20. Woodley et al. (1975) reported average differences of 9 percent when measuring thunderstorm rains in gages located 2 m apart. The gages were of similar type and had the same exposure. In a similar experiment Huff (1955) found a difference of only 2 percent, while Joss and Gori (1978) reported a standard error of 6 percent on a variety of rainfall types.

21. The major source of catchment error is turbulence of air around the orifice of the gage. Larson and Peck (1974) note a 12-percent deficiency in gage catch with a wind of 5 m/sec and a 19-percent undercatch with wind speeds of 10 m/sec. In the strong outflow regions of thunderstorms the undercatch may be as great as 40 percent.

22. Rain gages are essentially point measurements of precipitation. Values reported may not be representative of a large geographical area surrounding the gage. Therefore, sampling errors depend on the number and distribution of gages, the size of the area, the length of sampling time, and the spatial variability of the precipitation event.

23. In programs such as FACE (Woodley et al. 1975) it is assumed that a dense rain gage network gives the true average precipitation. Differences between the dense network and the surrounding gages are referred to as the sampling error over the entire study area. In general, agreement between the radar and rain gage precipitation totals increases with decreasing radar range. Further, the agreement increases with increasing

study area, rain gage density, rainfall amounts, and time periods sampled (Linsley and Kohler 1951; Huff 1971).

24. Wilson (1970) demonstrated that the combined use of radar and rain gages to measure rainfall was superior to either used separately. If more than one gage is available for calibration purposes, he proved that it is best to apply individual calibration factors rather than to derive one calibration factor from all gages. These findings, in conjunction with the development of the digital radar, have made installation of an operational system for the measurement of rainfall more feasible.

25. Woodley et al. (1975) used a daily areal average correction factor in measuring rainfall from Florida air mass convective storms because of the large spatial gradients of rainfall within such storms. Under such a precipitation regime the gage catch may not represent the mean precipitation over the area because of the likelihood of rainfall pattern differences between the gages. The disadvantage of such a technique is that the final rainfall field does not always agree with the gage measurements at individual sites.

26. Most of the work done to determine the density of a rain gage network necessary for a predetermined accuracy of rainfall has been focused on convective type storms. Further, the primary goal of the work was to investigate the results of weather modification experiments. Woodley et al. (1975) studied the problem of determining the number of gages necessary to equal the accuracy of the radar estimates of Florida summer convective storms. Table 2 presents the optimum method of rain measurement when the rainfall must be within a factor of 2 of the true mean 99 percent of the time.

27. The goal of the study was to measure the rainfall from individual clouds. Unless one was willing to wait for the development of the cloud over the rain gage network, radar adjusted by rain gages was the only way to evaluate the rain production. Results of the study indicated that it would take 90 rain gages to equal the accuracy of a radar adjusted with a network of 40 gages.

28. Huff (1970, 1971) stated that dense networks can accurately measure mean areal rainfall amounts. He developed a regression equation which indicated that the relative errors in mean areal rainfall estimates increase with decreasing gage density, precipitation amount, and storm duration. His conclusion was that for Illinois thunderstorms, area-mean gage rainfall amounts should be accurate to within 5 percent for gage densities greater than one gage per 50 km^2 and for rainfall rates greater than 10 mm hr^{-1}. Further, area-mean rainfall measurements should be accurate within 10 percent for gage densities greater than 1 per 160 km^2 and for rainfall rates greater than 4 mm per hr^{-1}. Huff's work indicates that necessary gage densities can be established to meet rainfall measurement requirements. Considerations like cost, ease of gage servicing, personnel, etc. must be the controlling factors in deciding the method of rainfall measurement to be used.

Table 2
Optimum Method of Rain Measurement with the Requirement that the Rainfall Be Within a Factor of 2 of the True Mean 99 Percent of the Time

Type of Measurement Choice	Required Rain Gage Density, km^2 Per Gage		Best and/or Most Practical
	Without Radar	Supplemented with Radar	
Individual cloud rainfall anywhere	13	26	Gages, but radar far more practical
Area rainfall over fixed areas (570 km^2)	13	26	Gages
Area rainfall over 1.3×10^4 km^2	143	143	Gages or radar depending on terrain, budget, and personnel

Source: Woodley et al. (1975).

29. Brandes (1975) described a technique of combining gage and radar rainfall estimates. His method retains the point accuracy of the rain gages and the good spatial coverage of the radar. The major steps in Brandes' technique are

a. Gage-radar rainfall ratios (G/R) are calculated at gage locations using evenly weighted radar data from within a fixed radius from the radar. The radar radius chosen is small relative to the gage spacing.

b. Radar rainfall data are thresholded and converted to a cartesian grid having a grid spacing roughly equivalent to radar data spacing.

c. The gage rainfall data and G/R ratios are transformed to the same Cartesian grid as the radar data. The weighing factor used reflects the grid density.

d. The adjusted radar rainfall field is obtained through a grid-by-grid multiplication of the G/R ratio and the radar rainfall field.

e. A final rainfall field is constructed using the gage and adjusted radar rainfall fields. The final rainfall estimate is set to 100 percent of the gage value at gage locations and linearly interpolated to 100 percent of the adjusted radar value at some fixed distance from the gage location.

30. Hildebrand et al. (1979) conducted a study using a modified Brandes technique on two data sets in an attempt to assess the accuracy of the mean rainfall correction factor. The data sets were from the High Plains Experiment (HIPLEX) and the Chicago Hydrometeorological Area Project (CHAP). The latter data set was used in two separate routines, one directed at real-time measurement of rainfall and its application to urban hydrological problems and the other at the problem of measurements of rainfall over large bodies of water. Results of the CHAP study indicate that the current combination of radar and rain gage data are no more accurate than gages alone if the gage density is on the order of 1 gage/100 km^2, or greater. For gage densities of approximately 1 gage/250-300 km^2 and for the Illinois climate, the combination

radar-rain gage estimates are slightly more accurate. A similar improvement in rainfall estimates was not apparent in the analysis of the HIPLEX data.

31. Austin (1980) stressed the importance of differences in modes of sampling and time integration as causes of variations in rainfall measurements made by radars and rain gages. The rain gage measurement represents a point total of precipitation while the radar typically averages precipitation over 5 to 10 min and over a radar bin 1 deg wide and 1 km long. Stout and Mueller (1968) compared the area of the radar beam and the rain gage. With a 1-deg horizontal bandwidth and a microsecond pulse rate, the radar will sample a volume over an area of 26,000 m^2 while the rain gage samples an area on the order of 0.07 m^2. In processing, the radar data are routinely converted to Cartesian maps with a 4- or 2-km resolution. One result of this averaging can be a spatial smearing of the radar data which can cause a significant underestimate of the peak rainfall amount.

32. Time intervals between radar maps are typically 10 min. It is possible for an intense storm to move several kilometers during this interval. Normally storms are not advected during this time period. Under these conditions the radar will give an overestimate of precipitation when intense echoes correspond to the map time and an underestimate when they do not.

33. Wilson and Brandes (1979) concluded that the primary causes of error in the radar measurements of precipitation result from variations in the Z-R relation caused by microphysical and kinematic processes that affect the drop-size distribution and drop- fall speeds. These variations can occur within a single storm or between storms. The radar has a tendency to overestimate light rainfalls and to underestimate heavy rainfalls.

34. Successful integration of radar and rain gage measurements requires the careful calibration of the radar. Independent checks for system biases must be made by comparing radar estimates with measurements from rain gage or disdrometer data.

PART III: CURRENT AND PROJECTED SYSTEMS FOR REAL-TIME FORECASTS OF PRECIPITATION

35. Development of an integrated radar output has stimulated the creation of numerous programs for the quick utilization of these rapidly changing radar products. In the early stages of development the only integration took place on the Plan Position Indicator (PPI) scope. For many years, analog techniques for integration, scan conversion, data transmission, and display were used. These methods had serious technical problems such as lack of stability of analog equipment, distortion and interference which could corrupt analog transmissions over telephone lines, and limited ways to manipulate the data further.

36. Digital processing has led to the development of large networks of radars that can provide quantitative data in real time to remote terminals. Among the advantages of this technology are:

a. Rainfall accumulations can be integrated areally and temporally.

b. Very short-term objective forecasts are possible.

c. Data from a number of radars can be composited to give a unified presentation of precipitation distribution over large areas.

d. Readily accessible banks of precipitation data can be developed for climatological and research purposes.

37. Development of the network systems was based on the premise that a variety of products would be needed by the user community. Among these products are those that depict the three-dimensional structure of the atmosphere. This includes a Constant Altitude Plan Position Indicator (CAPPI) map of the storm. Other products include two-dimensional surface precipitation and Range Height Indicator (RHI) views of the vertical structure of a storm. Precipitation maps can be computed at any convenient time interval and scale. Such maps can be of great utility to the field hydrologist.

38. A diagrammatic view of a system developed in the United Kingdom is shown in Figure 1 (Ball et al. 1975). Two major features are apparent. First, a minicomputer located at the radar site carries out a variety of tasks such as data integration, organization, and bookkeeping. Second, a color television monitor pictorially displays the processed data.

39. Figure 2 (Ball et al. 1975) displayed the division of each azimuth sector into range cells and bins by the analog to digital convertor (ADC) and hardware averager and into azimuth cells by the number of radar transmissions accepted. The precision with which the mean signal is determined is a function of the number of independent samples integrated. This, in turn, is related to the rate of spin of the antenna.

40. Currently a number of programs are undergoing development. These programs have such names as FRONTIERS, SHARP, CHAP, D/RADEX, RADAP II, and NEXRAD. Each will be discussed in some detail.

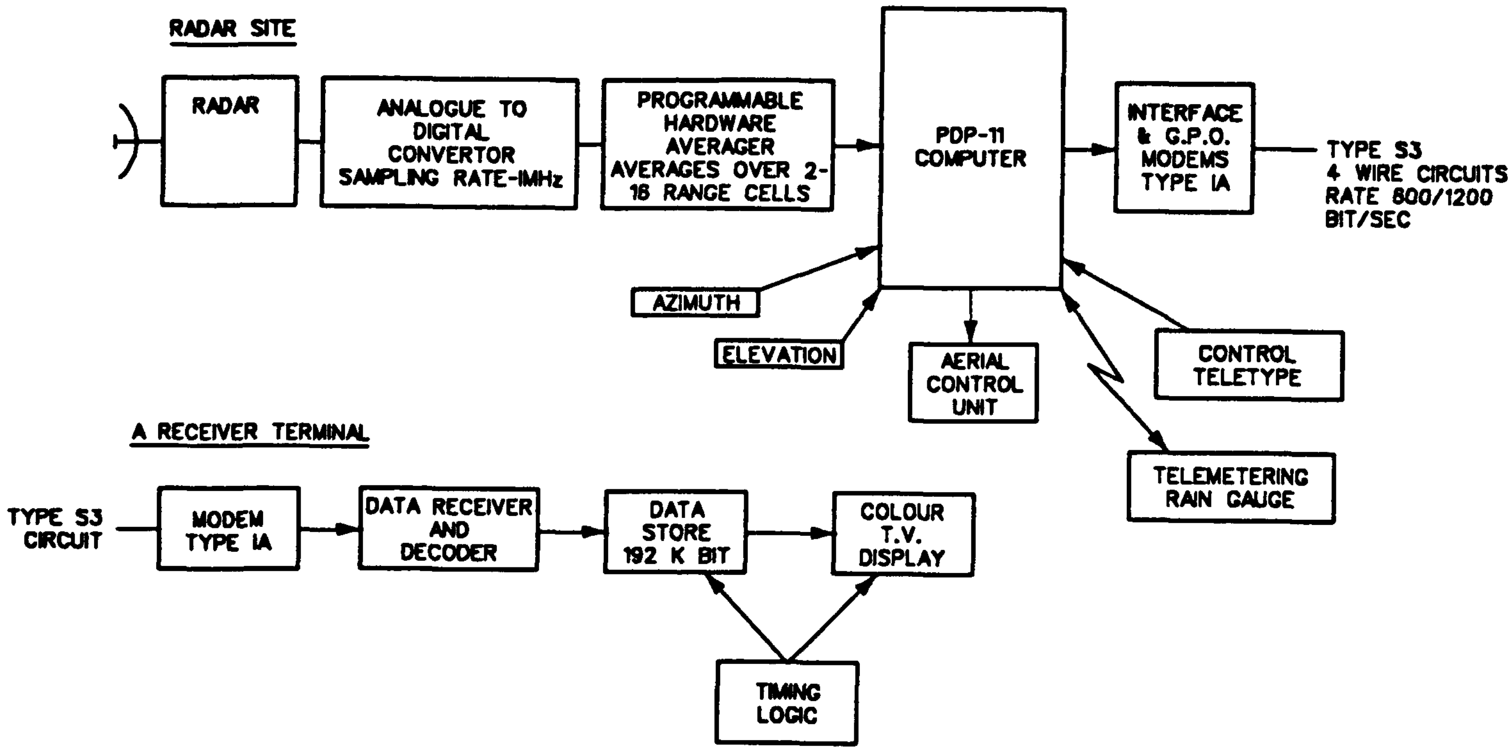
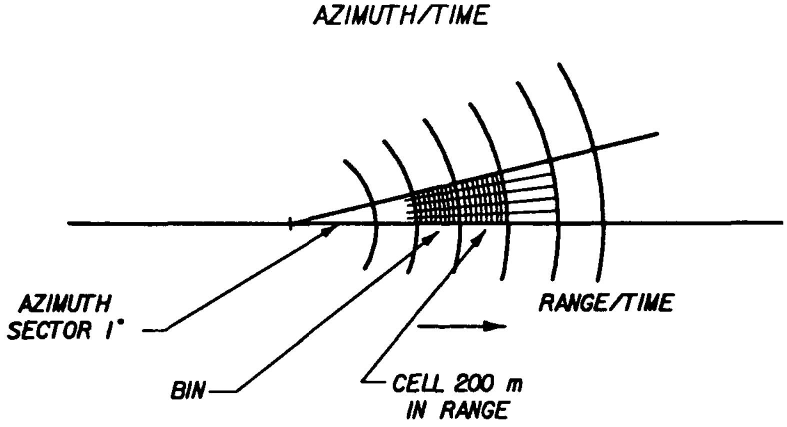
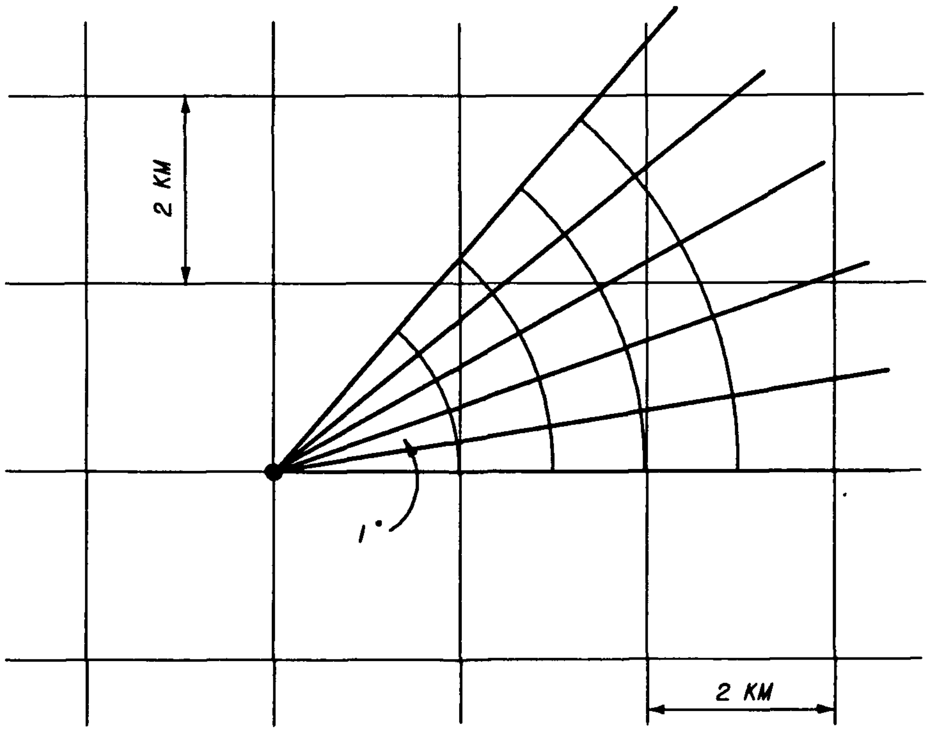


Figure 1. Overall outline of prototype system RR/R 31/9985 (Ball et al. 1975)



a. The division of each azimuth sector into range cells and bins by the ADC and hardware averager, and into azimuth cells by the number of radar transmissions accepted



b. Illustration of the conversion from polar to 2-km Cartesian coordinates. Similar computation applies for conversion to 5×5-km grid

Figure 2. Divisions of radar plots by azimuth and time with conversion to Cartesian coordinates (Ball et al. 1975)

FRONTIERS

41. One of the earliest programs was developed by the Royal Signals and Radar Establishment (RSRE). The program is entitled FRONTIERS, an acronym for Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite. Browning (1979) described the program as a strategy for using radar and satellite imagery for very short-range (0 to 6 hr) precipitation forecasting. The goal of the program is the total integration of radar and satellite data in a highly automated manner. All data are in a format adaptable to objective extrapolation procedures. A crucial element in the program is a strong man-machine mix in both analysis and forecasting.

42. The program emphasizes the analysis of current weather and its extrapolation into the near future. Such an analysis should lead to a better understanding of mesoscale meteorological events and to the generation of a new series of numerical weather prediction models for this scale.

43. In 1979 the RSRE began operation of a pilot program entitled the Short Period Weather Forecasting Project. Its aim was to develop ways of exploiting radar and satellite imagery in conjunction with conventional weather data as a means of improving short range forecasts. This pilot program led to the establishment of semi-operational facilities to provide integrated fields of rain and cloud from a network of radars and satellites. At the present time, the program uses four radars that satisfy one of the requirements for short-range forecasting (i.e., a large area of surveillance with overlapping coverage). Collier (1980) stated that two of the radars are older 10-cm devices, another is an older 5.6-cm device, and the fourth is a new, highly automated 5.6-cm radar. All four are capable of producing a precipitation map at 1-min intervals with a minimum resolution of 1 km. Normally the project uses a 5-min time span and a 2- or 5-km spacing.

44. Satellite data are supplied by Meteosat, a geostationary satellite capable of providing infrared (IR) and visual cloud imagery every 30 min with a resolution of 6 km E-W and 12 km N-S. Only IR images are available during the nighttime hours. The ground station for Meteosat is Dramstadt, West Germany, where the data are processed, archived, and then redistributed in near real-time via the satellite. These data are remapped and converted to a digital format similar to the radar data. The basic cell size for both data sets is 5 by 5 km.

45. A variety of computers are employed within the system, with functions as outlined above. A minicomputer is used at each radar site. Several computers are located at Malvern, the main headquarters of the RSRE. The network computer receives data from the individual radar sites every 15 min, composites these data, and develops an archive on magnetic tape. The radar composite is then passed on in near real-time to the display computer, which reformats and merges the composite radar and digital satellite data for analysis by forecasters at Malvern. Certainly satellite cloud images are inferior to radar data as a means of inferring rainfall patterns; however, satellite data are valuable for extending the range of coverage beyond the radars and thereby can give advance warning of rain systems as they approach the United Kingdom.

46. The primary emphasis of the program has been on the detection and development of mesoscale advecting systems. This approach is entirely appropriate as systems of this type are the primary weather producers of the region. Hill, Browning, and Bader (1981) demonstrated that these frontal systems display considerable persistence and can be tracked for hundreds of kilometers, even in areas of high orographic influence.

47. Interest in the products, both real-time forecasts and archived data sets, has led to the development of new dissemination formats that allow for automatic transmission over standard telephone lines. The time delay between the receipt of the raw data to the issuing of the forecast should be between 15 and 30 min. Products may include accumulated rainfall over 1 hr, 3 hr, or the life of the storm, as well as hourly forecasts of total precipitation up to 6 hr into the future.

48. FRONTIERS has been of interest to numerous water authorities hoping to apply off-line case studies of hydrologically interesting events as well as to adapt a better means of water management in their catchment areas. The Agriculture and Hydrometeorology Branch of the Meteorological Office at Bracknell has requested hourly data which will be used to assess rain gage network densities necessary to support the development of the entire FRONTIERS Program.

49. An outgrowth of the program is a research effort to improve the understanding of the structure, physical mechanisms, and predictability of rain. Using the equipment outlined above and incorporating normal meteorological parameters, including radiosonde information and the input from 40 recording rain gages, a vast database has been developed in the archives of the Meteorological Office. This information provides the necessary input into the development of new numerical weather prediction models that in turn lead to a better understanding of the causes and distribution of precipitation.

50. The pilot program was scheduled to run through the 1980's, with one objective being to determine the optimum mix of man and machine. Table 3 outlines the overall components of the integrated forecast system.

SHARP

51. A second foreign program is the Canadian effort called SHARP, Short-term Automated Radar Prediction. Bellon and Austin (1978) described the results of a 2-year study of real-time operation of the short-term precipitation forecasting procedure. Their procedure consists of making digital, constant-altitude, plan position indicator (CAPPI) Cartesian maps, using a minicomputer on-line with the radar set, and matching echo patterns 1 hr apart. Matches are based upon a pattern recognition technique which finds by cross-correlation the best match between the current map and the one stored from the previous hour. They employ a "status quo" assumption that does not allow for changes in echo shape or differential movement of the storm. Bellon and Austin (1984) reported that the major cause of poor forecasts is not due to error in the forecast displacement but rather to unpredictable configurations of radar echo patterns as they undergo growth or decay during the forecast period.

Table 3
The Principal Components of an Integrated Forecast System Incorporating a Weather Radar Network

Principal components	Functions	Products Available in Near Real-Time	How Derived
Unmanned radar sited at locations with good horizons (own set of telemetering rain gages for real-time calibration)	Rain surveillance with on-site computers for pre-processing the radar data	1) Surface rainfall distribution from individual radars without quality control 2) Areal integrations in river subcatchments	Automatic
Radar compositing and mesoscale analysis center	1) Quality control to eliminate spurious echoes 2) Derivation of a composite rainfall map using data from all radars 3) Analysis of satellite data in terms of surface rainfall to extend the coverage beyond the range of the radars	Quality-controlled large-area composite maps of surface rainfall Simplified rainfall data in a format suitable for input to a mesoscale NWP model	Combination of objective and subjective procedures implemented using interactive computer-driven video display techniques
Central Forecast Office	As at present, plus prep of 3- to 24-hr forecasts using mesoscale NWP model	As at present, plus prep of 3- to 24-hr mesoscale forecasts	Mainly automatic
Regional Meteorological Offices	1) Preparation of forecasts 2) Tailoring and dissemination of the actual and forecast rainfall information to local users	Tailored forecast and actual rainfall information dissemionated in picture, worded, or computer-compatible formats	Combination of objective and subjective procedures implemented using interactive computer-driven video displays

Source: Browning (1980).

52. SHARP was designed primarily to yield 2-hr forecasts every hour. As the system is developed, additional products such as echo-top plan position indicator maps, real-time CAPPI's of varying ranges and resolution, vertical cross-sections, and cumulative precipitation maps for hydrologic modeling will be developed.

53. The SHARP technology was applied to 37 weather sequences that passed over the city of Montreal. Some 200 hr of data taken over a 4-year period were used to evaluate the radar precipitation forecasts. The radar-estimated accumulations were found to have an inherent error of 25 percent; half-hour forecasts had an error of 50 percent, and the 3-hr forecasts, some 60 percent. Errors were significantly reduced if a tolerance of 30 min was permitted. This adjustment allowed for acceleration or deceleration of the storm as it moved over the catchment area.

54. During the development of the analysis algorithms, the problem of anamolous propagation was investigated. Bellon and Austin (1977) discussed the diurnal distribution of anomalous propagation which has always been a very difficult problem for the radar meteorologist. They found the phenomena reached a maximum intensity at approximately 11 p.m. with a secondary maximum at 7 a.m. It was essentially nonexistent between 11 a.m. and 5 p.m. In their 1978 report, the authors stated that their pattern recognition technique could recognize the phenomena and automatically issue a warning of its presence.

55. A major outgrowth of the SHARP Program was the development of a radar climatology of surrounding areas. Regions of storm development and dissipation were clearly established. Growth areas could be tied to geographical features such as the Laurentian Hills and the Adirondack Mountains. Small negative regions (dissipation zones) were related to Lake Champlain, Lake St. Pierre, and the area northeast of Ottawa.

56. The SHARP forecasts of precipitation were found to be very useful to both operational meteorologists and hydrologists.

CHAP

57. In the mid-1970's the Illinois Water Survey began designing and developing a comprehensive hydrometeorological project in the Chicago area called the Chicago Hydrometeorological Area Project (CHAP). Huff and Changnon (1977) describe the two phases of the program. The initial phase was completed in the spring of 1976, culminating in a major report that recognized the importance of the time-space distribution of heavy storm rainfall over a highly urbanized area. These storms can place a great stress on storm sewers and other types of hydrologic structures susceptible to flooding.

58. Phase I included a review of all historic rainfall data on the urban area. Special emphasis was placed on the data from recording rain gages in the six northeast Illinois counties between 1950 and 1970. It was recognized that Lake Michigan and the inner urban area caused an inadvertent modification of the weather. The studies investigated the seasonal and diurnal distribution of storms, synoptic weather types associated with

each storm, general shape characteristics of heavy rainfall patterns, the time between successive severe rainstorms, storm movement, the spatial distribution of heavy rainstorm centers within the region, and the relation between the frequency distribution of point and areal mean rainfalls.

59. The final report highlighted several findings. There was a trend for the storms to be heavier over the north central and southern parts of the city and to be less intense near the lake and in the northeastern suburbs. Flood-producing storms occurred most frequently in the summer, with a peak in July. Further, there was a need for more spatial information on rainfall in and around Chicago, a need that led to Phase II of CHAP.

60. Huff and Towery (1978) outlined the major Phase II objectives:

a. Develop a real-time, prediction-monitoring system for storm rainfall using a combination of weather radar and telemetered rain gage data.

b. Determine precipitation measurement requirements for hydrologic design, operation, and modeling purposes.

c. Define the space-time characteristics of heavy rainstorms in the Chicago urban area.

d. Establish methods for applying the Chicago findings to other cities.

61. The basic components of the CHAP field measurement program included a network of 320 rain gages spread uniformly over 10,000 km^2 and two sophisticated weather radar systems for obtaining real-time information on storm parameters pertinent to optimizing water resource management. The main Hydrometeorological Operational Tool (HOT) radar system included a 10-cm radar with an associated signal processor and minicomputer for rapid digitization of the radar-indicated rainfall information. The radar system was coupled with 22 telemetered rain gages operated by the Metropolitan Sanitary District (MSD) of Greater Chicago. Radar estimates were frequently adjusted by the Brandes technique (paragraph 29). Huff, Changnon, and Vogel (1980) stated that an average error of estimate of approximately 20 percent is about the best that can be achieved if the radar rainfall estimate is not adjusted with rain gage data.

62. A demonstration project of the real-time monitoring and prediction capabilities of the system was conducted during July and August of 1979. Every 30 min, radar-indicated rainfall amounts over the city plus forecasts for the next 30, 60, and 120 min were transmitted to the MSD. The CHAP Z-R relation ($Z = 300R^{1.35}$) was used to obtain the radar-estimated storm amount. The greatest percentage differences between radar and rain gage occurred with rains of less than 5 mm.

63. Forecasts of areal average rainfalls were made with the minicomputer by extrapolating the radar echoes forward in time. Allowance was made for the echoes to change their area and intensity according to trends in the preceding 10 min. The operator was able to modify storm motions and growth rates of individual clouds.

64. The radar-man forecast technique could predict the onset of precipitation within 30 min. Results from the demonstration stress the need to employ skilled operators, including an experienced radar meteorologist, to effectively utilize radar as a prediction tool for heavy rainfalls.

D/RADEX

65. In the United States, the National Weather Service (NWS) has been developing and testing procedures to process digitized weather radar data into useful meteorological and hydrological products. Begun in the early 1970's, this work led to the development of the Digitized Radar Experiment (D/RADEX). By 1976, the D/RADEX was installed and in operation at five sites: Stephenville, TX, Oklahoma City, OK, Monet, MO, Kansas City, MO, and Pittsburgh, PA. Newly developed products were tested at the Pittsburgh site before being included on the menus at other locations.

66. Saffle (1976) described the status of the D/RADEX Operating System (DROS), giving examples of the various types of meteorological products generated. The main component of the DROS is a minicomputer with 24K words of memory. The radar operator communicates with the computer via a keyboard-printer terminal. The interface between the computer and the radar is the Video Integrator and Processor (VIP), which integrates the reflectivity intensities over 18 radar pulses, and outputs a value for each nautical mile range increment. Antenna rotation speed is normally 3 rpm. Therefore, the integrated sample area is 1 nautical mile* by 2 deg. In DROS, an analog-to-digital converter transforms the data into digital values from 0 to 255.

67. Normally, DROS collects one scan of data at 0-deg antenna tilt every 12 min. A scan consists of 180 radials of data at 1-nautical-mile range increments from a range of 10 to 125 nautical miles. Each data point is converted from a value in the range of 0 to 255 to a value in the range of 0 to 9. For intensity display purposes, the data are further reclassified to a range of 0 to 6. The values represent the same echo intensity as those presented to the PPI by the VIP. Relations between rainfall rates with radar power returned, VIP levels, and D/RADEX levels are shown in Table 4.

68. Several products are available from DROS. The basic product is called the BSCAN, a display of a scan of echo intensities by range and azimuth. The BSCAN presents the greatest possible areal resolution since the display elements represent the same area as the basic sampled data.

69. A second product available through DROS is a standard grid map. This display looks like a standard PPI view of the region with each grid box 3 nautical miles EW by 5 nautical miles NS. The intensity map converts each scan from the polar coordinates input to rectangular coordinates in the DROS standard grid. This map is essentially a digital form of the PPI display. The DROS will automatically produce a new intensity

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

map whenever the maximum intensity increases or decreases by one VIP level. If the VIP level is equal to or greater than 4, the intensity map will be drawn on each scan.

Table 4
Comparison of Rainfall Rates with Radar Power Returned, VIP Levels, and D/RADEX Levels

Rainfall Rate in./hr	Log Z	Threshold Levels VIP	D/R
0.2 @ 125 nautical miles		1*	
0.02	1.83		1
0.05	2.47		2
0.1	2.95	2	3
0.2	3.43		4
0.5	4.07	3	5
1.0	4.55	4	6
2.0	5.03	5	7
5.0	5.67	6	8
10.0	6.15		9

Source: Saffle (1976).
* Not range corrected.

70. Another DROS product is the System Movement Vector. This is a plain-language statement regarding the speed and direction of movement of a portion of the echo pattern above a specified VIP level.

71. One of the most important DROS products is the Rainfall Accumulation Map. The length of the accumulation period can be varied depending upon the needs of the user. River Forecast Centers are normally given 3-hr accumulations for input into their models. The Flash Flood Monitoring Program uses the Rainfall Accumulation amounts for each box of the DROS standard grid for the entire storm period and produces a plain language alert message when the total exceeds a pre-selected amount. This message is automatically displayed locally and transmitted to selected remote users such as River Forecast Centers and Weather Service Forecast Offices.

72. Two other products are typically produced by DROS. One of these, Echo Tops, is produced twice each hour and is the result of successive scans of data at 2-deg antenna elevation increments from base elevation to a maximum of 22 deg. Echo Tops calculates the height and location of each no-zero point. The program automatically corrects for the earth's curvature and slant range versus earth range. The last product is the Vertical Integrated Liquid Water Map (VIL). Elvander (1976) states that the VIL is an excellent predictor of severe weather.

RADAP II

73. In 1976 the D/RADEX experimental system was replaced by the RAdar DAta Processor (RADAP II) program which provided a powerful computer system as an operational tool at selected NWS primary weather radar sites. By August 1986, a total of 11 RADAP II sites were in operation (Figure 3). It should be noted that the western group of stations furnishes coverage over approximately 90 percent of the Arkansas River drainage system, which is under the supervision of the Tulsa, OK, River Forecast center.

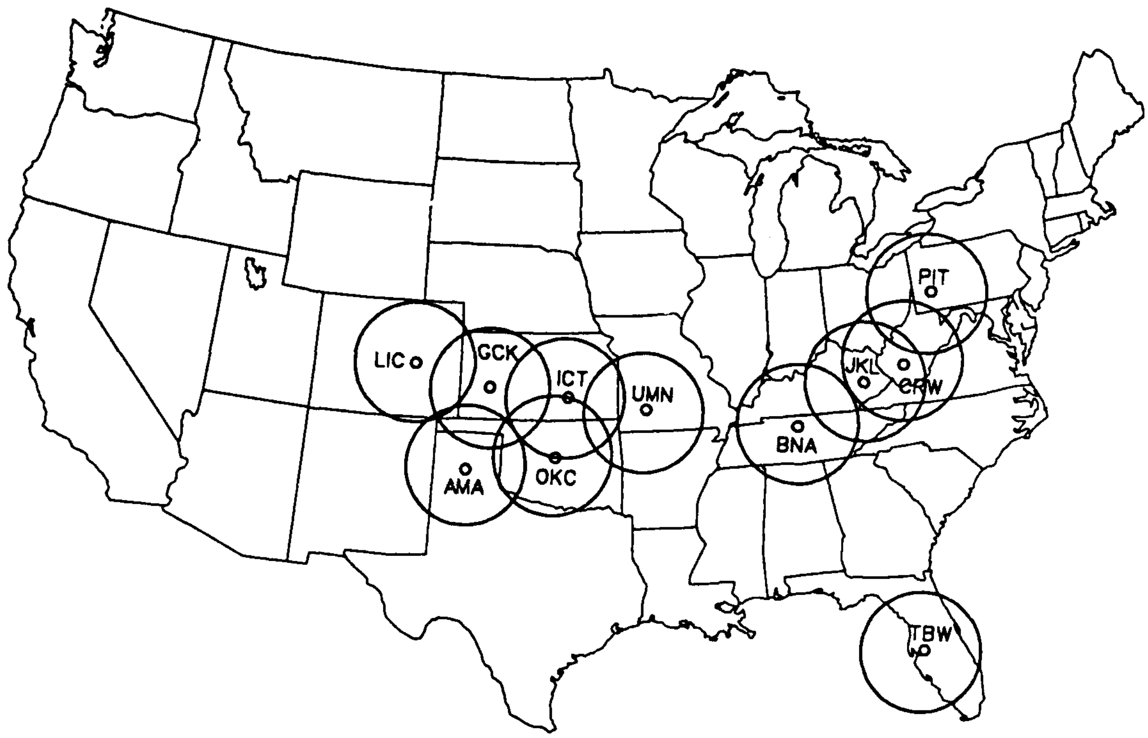


Figure 3. National Weather Service RADAR II sites as of August 1986

74. RADAP II was designed to serve the needs of many different user groups, primarily meteorologists and hydrologists at the Weather Service Forecast Offices, Weather Service Offices, and River Forecast Centers. Another major user is the System Development Office's Techniques Development Laboratory, which formulates short-range prediction models and procedures from the data. The Hydrologic Research Laboratory's Radar Hydrology Group is using the data in the Hydrologic Rainfall Analysis Project to improve the accuracy and timeliness of flood forecasts. Such forecasts are highly dependent upon the rapid availability of high quality digital radar data. The National Flash Flood Program is developing and testing a multistate hydrologic network which includes digital data input from the RADAP II station at Jackson, KY.

75. Greene et al. (1983) stated that initially the RADAP II system will generate the same products as those generated under the D/RADEX system. It is anticipated that as development of the system continues, new products will become available that will more nearly match those envisioned for NEXRAD. The RADAP II program, then, serves as a transition between the pioneering work of D/RADEX and the much more ambitious NEXRAD System.

76. Figures 4 and 5 show the general equipment configuration for the RADAP II system. The design criteria for RADAP II specified that the computer system had to be compatible with D/RADEX. A second constraint was that graphics displays would be available. It was believed these displays would lead to a greater utilization of the digital radar data by the radar operator and operational forecaster. The development of these graphics will serve as a bridge to the NEXRAD display products.

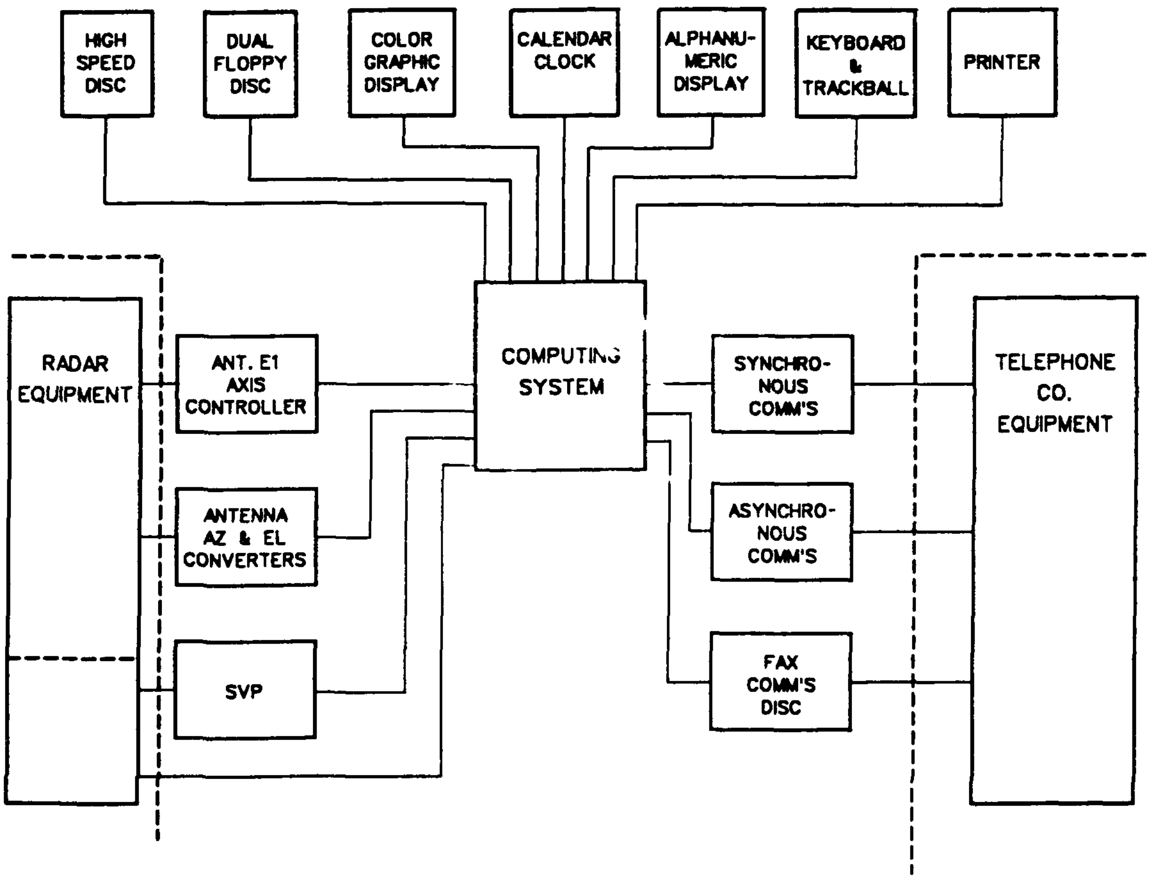


Figure 4. RADAP hardware

77. Winston and Ruthi (1986) found the Severe-Storm Detection Algorithm of RADAP II very useful in the operational environment. They believed that the frequently updated outputs from the RADAP II algorithm could provide important guidance to the operational forecaster.

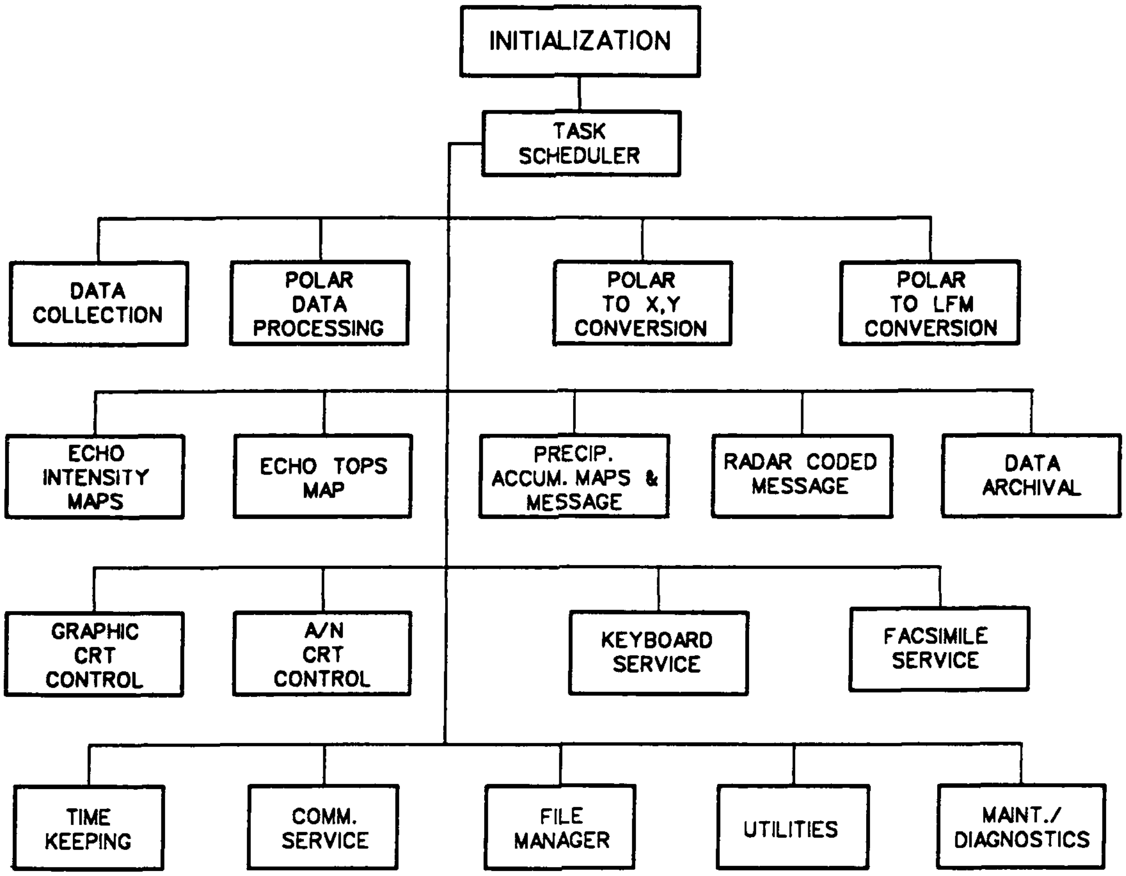


Figure 5. RADAP II operational software functions

NEXRAD

78. A major upgrading of the programs developed under D/RADEX and RADAP II, the NEXRAD System is designed to meet the needs of the nation well into the 21st century. NEXRAD is a joint program being conducted by the Departments of Commerce, Defense, and Transportation. Bonewitz (1981) gave an excellent overview of this project. NEXRAD incorporates the application of the Doppler principle, using solid state technology with improved communication, display, and data processing devices.

79. Golden (1984) divided the program into four phases:

a. **System definition**: In February 1982, three contracts were awarded to prepare concept reports and proposals for validation. These contracts terminated in December 1982.

b. **Validation**: In May 1983, Sperry and Raytheon were awarded contracts to develop pre-production models of their designs.

c. **Limited production**: The first 10 units are to be deployed starting in 1989.

d. **Full-scale production**: This phase is to continue until 1992. It is anticipated that the system will include between 140 and 160 radar sites. There will be complete coverage of the conterminous United States and Puerto Rico.

80. The three functional areas in the NEXRAD System are the Radar Data Acquisition (RDA) subsystem, the Radar Products Generation (RPG) subsystem, and the Principal User Processor (PUP) subsystem.

81. The Radar Data Acquisition (RDA) subsystem consists of the antenna and drive system, transmitter, receiver/exciter radar signal preprocessor, tower and radome, and a maintenance control center. This subsystem represents approximately 60 percent of the cost of the system. In addition to automated monitoring and error detection, general characteristics of this subsystem are listed in the following table.

Table 5
Radar Data Acquisition Subsystem Specifications

Frequency	2.7-3.0 GHz
Beam width	1 deg (max)
Range (reflectivity)	460 km
Range (velocity)	230 km
Transmitted power	1 megawatt (pk), 2 kilowatts (avg)
Pulse length	1.6-1.7 and 4 μsec
Pulse repetition frequency	250-1,250 pulses per second
Clutter cancel (ref)	30 dB
Clutter cancel (Vel)	50 dB

82. The advantages of the Doppler weather radar were demonstrated during the Joint Doppler Operational Project occurring in 1978 and 1979 using the Doppler radar facility at the National Severe Storms Laboratory in Norman, OK. Results of the project showed that:

a. The Doppler capability is superior to conventional radar in that it results in an increased lead time for tornado warnings, reduced false alarm rates for tornadoes and thunderstorms, and improved probability of detection of severe thunderstorms.

b. The narrow 1-deg beam width distinguishes between severe and non-severe thunderstorms at ranges out to 350 km and separates tornadic from non-tornadic storms at ranges closer than 230 km.

c. The system provides precise location of weather signatures, facilitating warnings specially directed to small areas under threat.

d. The NEXRAD System significantly improves the ability to support flash flood warnings by more accurately estimating rainfall. The addition of digital processing and the improved resolution of NEXRAD are important factors in achieving an estimated 45-76 percent improvement over today's weather radars.

83. Golden (1984) stated that the interconnection of the RDA and RPG will be provided over a wideband communications link. The exact type of link will depend upon terrain, separation distance, and other factors. Current technology includes fiber

optics, microwave line of site, and coaxial cable. Data compression/compaction will be used to reduce the communications load. Emphasis will be placed on the development of highly reliable equipment operating under adverse weather conditions.

84. NEXRAD is as much a computer system as it is a radar system. The RPG will absorb approximately 20 percent of the total program budget. The operational forecaster will be provided with a vast array of information. Meteorological algorithms and derived products for NEXRAD are listed below.

a. Meteorological algorithms:

Storm segment
Storm centroids
Storm tracking
Storm position forecast
Storm structure
Hail
Mesocyclone
Echo tops
VIL
Severe weather probability
Shear
Velocity azimuth display
Transverse wind
VVP (velocity volume processing)
Precipitation preprocessing
Precipitation range
Precipitation accumulation
Precipitation adjustments
Precipitation products
TVS (tornado vortex signature)
Gust front
Turbulence
Convergence/divergence
CAPPI (constant altitude PPI reflectivity and velocity)
Flash flood

b. Base products:

Reflectivity maps
Velocity maps
Spectrum maps

c. Derived products:

Shear, contour
Shear, high resolution
Composite reflectivity map

Composite reflectivity contour
Echo tops map
Echo tops contour map
Transverse wind
Severe weather alert maps
Velocity azimuth displays
Surface rainfall accumulation maps
Storm total rainfall
Combined moment map
Reflectivity map (CAPPI)
Velocity map (CAPPI)
Hazardous aviation contour
Range height map
Weak echo region
Velocity volume processing
Vertically integrated liquid

d. Alphanumeric products:

Severe weather alert message
Free text message
Radar-coded message

e. Derived data array products:

Hazardous aviation weather data
Reflectivity, radial data
Velocity, radial data
Hourly digital radar rainfall estimate

85. The Principal-User Processor (PUP) subsystem is the operator interface to NEXRAD. Of the cost of the total system, 20 percent will be spent on this subsystem. Features of the PUP subsystem are summarized below.

86. The PUP subsystem will consist of two high-resolution color graphics and one alphanumeric display system. A quarter-screen display capability will permit simultaneous viewing of four different products on a single screen. The operator can change data display resolution and change magnification to improve analysis of small-scale features. A large selection of background graphics will be available. The operator can provide alphanumeric annotation for a displayed image. Other features will include a time lapse capability for up to 72 images of selected products and the local storage of all products received for a 6-hr period.

Displays	2 color graphic, 1 alphanumeric
Resolution	640 by 512 pixels; 24 lines by 80 characters
Overlays	4 simultaneous, e.g., geographic, political, cultural, etc.

Features	1/4 screen display, magnification/ resolution change
Annotation	Alphanumeric plus 64 special characters and symbols
Time lapse	3 products pre-selected for time-la[illegible] [illegible]2-image sequence of selected p[illegible]
Local storage	A[illegible] [illegible]ts received for 6 hr

87. NEXRAD will be able to serve the operational meteorologist and hydrologist. It will be on-line during the coming decade and will be operational for at least 25 years.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

88. A considerable amount of information regarding radar-rain gage calibrations and related topics exists in the literature. In addition to that addressed in the main text, a significant number of references are presented in annotated form in Appendix A. Both sources were considered in reaching the conclusions and recommendations set forth below. Specific results and conclusions arrived at by the many investigators vary to a large degree because of differences in the settings and conditions under which investigations were made; nevertheless, some generally applicable statements can be made.

89. The use of weather radars for the acquisition of the areal distributions and amounts of precipitation has been going on since the 1940's. For many years these efforts were hampered by two factors: (a) there was no unique relation between the rainfall rate at the ground and the reflectivity value observed on the radar scope, and (b) there was no mechanism for the rapid integration of rainfall data into a useable format. With the advent of the digital radar in the 1970's, the last shortfall was effectively removed. However, the first problem still exists.

90. By developing a radar climatology for an area, some success at estimating precipitation events with radars has been reported. Development of a radar climatology involves the acquisition of data on rainfall amounts and intensities as a function of time of year, time of day, synoptic type, orographic influences, and related meteorological factors such as atmospheric stability. With this information available, radar meteorologists and operational forecasters can obtain a Z-R relation unique for a given weather situation and area. In all probabililty the Z-R relation cannot be extrapolated to other climatic types under different synoptic conditions: However, indications are that there is some consistency within climatic zones under similar synoptic conditions.

91. Rain gages are essentially point-measuring devices. As such, they cannot accurately depict the areal distribution of rainfall or area average amounts of rainfall unless deployed in high density networks. Most work on rainfall measurement accuracy as a function of gage density has been associated with convective type storm systems. At one extreme, Woodley et al. (1975) found that to determine rainfalls for individual clouds within a factor of 2 at a 0.99 probability level, the required gage density would be 1 per 13 km^2. At the other extreme, Brandes (1975) found that average storm rainfalls for a 3,000-km^2 basin could be determined within 21 and 24 percent for gage densities of 1 per 900 km^2 and 1600 km^2, respectively.

92. The effectiveness of radars for monitoring precipitation is largely a function of wavelength. A wavelength of 3 cm is unsatisfactory because of attenuation. A 5-cm radar is marginal in terms of its utility. A 10-cm wavelength appears to be optimal. With a well-maintained and finely tuned 10-cm radar, Smith et al. (1975) estimated areal rainfall totals over a season within 15 percent of rain gage estimates using a standard Z-R relation. For individual storms, however, several investigators indicated that

radar and rain gage estimates of rainfall will commonly vary by a factor of 2 or more using standard Z-R relations and no calibration of the radar with the rain gages.

93. There is a consenus opinion among investigators that rain gages and a radar can generally provide better data than either system by itself; this is true from two different aspects. First, a sparse network of rain gages augmented by a radar can provide improved estimates of area average precipitation amounts. For example, Wilson (1970) concluded that equivalent accuracies for convective storm totals could be determined with rain gages spaced at area intervals of 2,600 km^2 supplemented by a 10-cm radar as opposed to rain gage intervals of 650 km^2 without a radar. Collier, Harrold, and Nicholass (1975) noted that a radar calibrated to two rain gages provides average accuracies equivalent to that obtained with 10 rain gages over a 1,000-km^2 area for widespread uniform rain, or equivalent to that obtained with 50 gages for showery conditions. Second, a radar calibrated to rain gages can provide the areally and temporally distributed rainfall data required for hydrologic estimates associated with convective storm activity and small computational areas. Harrold, English, and Nicholass (1974) and Harrold, Nicholass, and Collier (1975) found that neither a network of 62 rain gages over a 1,000-km^2 area nor a 10-cm radar could provide adequate data for predicting runoff of sub-basins ranging from 20 to 100 km^2 in size. With hourly calibration to one rain gage, however, the radar could provide radar estimates which were adequate, in fact within 13 percent of optimized rain gage measurements. Because the Z-R relation can vary significantly within a storm (both areally and temporally), there is general agreement that the accuracy of rainfall estimates, particularly in terms of areal distributions, improves as a radar is calibrated to more individual gages.

94. In addition to providing better estimates of areal average rainfall amounts and the areal distribution of rainfall, radar has other advantages. The CHAP program demonstrated a capability for predicting the onset of precipitation within a 30-min time frame. Further, the radar can be used to make short-term forecasts of rainfall by extrapolating radar echoes forward in time and space. In the SHARP program, it was found that the radar-estimated 0.5-hr forecasts had an associated error of 50 percent and the 3-hr forecasts an error of approximately 60 percent. Errors were found to be significantly reduced if a tolerance of 30 min was permitted. This tolerance allowed for acceleration or deceleration of the storm as it moved over the catchment area.

Recommendations

95. Data necessary for the development of weather radar climatologies should be gathered and archived if the feasibility of real-time calibration with rain gages is in question; this recommendation holds for both military and civil applications. Archived data should include weather maps to indicate synoptic factors, radar records showing reflectivity values, and rain gage reports indicating time and intensity values. The radar climatologies will allow the operational forecaster to make estimates of rainfall without calibration to a rain gage in the field. The radar climatologies should be tested against actual precipitation events to assess their utility under field conditions.

96. Operational strategies for military tactical weather radars should be developed, tested, and evaluated. Field siting procedures should be included, which involve: (a) the deployment of the radar components with respect to one another, the terrain, and the forward line of troops, and (b) the registration of the radar to the military grid coordinate system. Procedures for minimizing and randomizing radar emissions should be developed; this is essential because of the number of emitters that will exist on the modern battlefield and the susceptibililty of emitters to enemy weapon systems. In addition, the optimal deployment of radar system components, the movement of components, and the use of backup or redundant components to reduce vulnerability to enemy fire should be examined. Finally, techniques for calibrating a weather radar system should be established. These should include the employment of optimized Z-R relations as noted in paragraphs 90 and 95 and the development of procedures for establishing radar-rain gage calibrations within a tactical environment.

REFERENCES

Ahnert, P. R., Hudlow, M., Johnson, E., Greene, D., and Dias, M. 1983. "Proposed "On-site" Precipitation Processing System for NEXRAD," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada,* pp 378-385.

Austin, P. M. 1980. "Some Comparisons of Rainfall Amounts Measured by Radar and with Rain Gauges," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL,* pp 431-437.

Ball, A., Clarke, J. L., Davy, B. D., O'Brien, M. J., Trigg, S. E., Taylor, B. C., and Voller, T. A. 1975. *A System for the Processing, Transmission and Remote Display of Data from a Weather Radar,* Royal Signals and Radar Establishment Memorandum No. 3032, Malvern, England, p 40.

Battan, L. J. 1973. *Radar Observation of the Atmosphere.* University of Chicago Press, Chicago, IL, p 324.

Bellon, A., and Austin, G. L. 1977. *The Real Time Test and Evaluation of "SHARP" a Short-Term Precipitation Forecasting Procedure,* Stormy Weather Group Scientific Report MW-91, MacDonald College, Quebec, Canada, p 57.

_____. 1978. "The Evaluation of Two Years of Real-Time Operation of a Short-Term Precipitation Forecasting Procedure (SHARP)," *Journal of Applied Meteorology,* Vol 17, No. 12, pp 1178-1787.

_____. 1984. "The Accuracy of Short-Term Radar Rainfall Forecasts," *Journal of Hydrology,* Vol 70, pp 35-49.

Bonewitz, J. D. 1981. "The NEXRAD Program—An Overview," Preprints: Twentieth Conference on Radar Meteorology, *American Meteorological Society,* pp 757-761.

Brandes, Edward A. 1975. "Optimizing Rainfall Estimates with the Aid of Radar," *Journal of Applied Meteorology,* Vol 14, No. 10, pp 1330-1345.

Brandes, Edward A., and Wilson, J. 1982. "Measuring Storm Rainfall by Radar and Rain Gage," *Thunderstorms: A Social, Scientific, and Technological Documentary, Instruments and Techniques for Thunderstorm Observation and Analysis,* Vol 3, National Oceanic and Atmospheric Administration, pp 241-272.

Browning, K. A. 1979. "The FRONTIERS Plan: A Strategy for Using Radar and Satellite Imagery for Very-Short-Range Precipitation Forecasting," *The Meteorological Magazine,* Her Majesty's Stationery Office, Bracknell, Berkshire, England, Vol 108, No. 1283, pp 161-183.

_____. 1980. "Radar as Part of an Integrated System for Measuring and Forecasting Rain in the UK: Progress and Plans," *Weather,* Royal Meteorological Society, Bracknell, Berkshire, England, Vol 35, No. 1, pp 94-104.

Carbone, R. E., and Nelson, L. D. 1978. "The Evolution of Raindrop Spectra in Warm-based Convective Storms as Observed and Numerically Modeled," *Journal of Atmospheric Science,* Vol 12 No. 12, pp 2302-2314.

Collier, C. G. 1980. "Data Processing in the Meteorological Office Short-Period Weather Forecasting Pilot Project," *The Meteorological Magazine,* Her Majesty's Stationery Office, Bracknell, Berkshire, England, Vol 109, No. 1295, pp 161-176.

Collier, C. G., Harrold, T. W., and Nicholass, C. A. 1975. "A Comparison of Areal Rainfall as Measured by a Raingauge Calibrated Radar System and Raingauge Networks of Various Densities," *Preprints: Sixteenth Conference on Radar Meteorology, American Meteorological Society, 22-24 April 1975, Houston, TX,* pp 467-472.

Eccles, P. J. 1978. "Automatic Flash Flood Warning from Dual Wavelength Radar-Are They Worth It?" *Preprints: Conference on Flash Floods: Hydrometeorological Aspects, 2-3 May 1978, Los Angeles, CA, American Meteorological Society*, pp 52-57.

Elvander, R. C. 1976. "An Evaluation of the Relative Performance of Three Weather Radar Echo Forecasting Techniques," *Preprints: Seventeenth Conference on Radar Meteorology, American Meteorological Society, 26-29 October 1976, Seattle, WA*, pp 526-532.

Golden, J. 1984. "NEXRAD News," National Weather Service, Silver Spring, MD, Vol 1, Nos. 1 and 2.

Greene, D. R., Nilsen, J. D., Saffle, R. E., Holmes, D. W., Hudlow, M. D., and Ahnert, P. R. 1983. "RADAP II, An Interim Radar Data Processor," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 404-408.

Harrold, T. W., English, E. J., and Nicholass, C.A. 1974. "The Accuracy of Radar Derived Rainfall Measurements in Hilly Terrain," *Quarterly Journal of the Royal Meteorological Society*, Vol 100, pp 331-350.

Harrold, T. W., Nicholass, C. A., and Collier, C. G. 1975. "The Measurement of Heavy Rainfall Over Small Catchments Using Radar," *Hydrological Sciences Bulletin*, Vol 20, No.1 pp 69-76.

Hildebrand, Peter H., Towery, N., and Snell, M.R. 1979. "Measurement of Convective Mean Rainfall Over Small Areas Using High-Density Raingages and Radar," *Journal of Applied Meteorology*, Vol 18, No. 10, pp 1316-1326.

Hill, F. F., Browning, K. A., and Bader, M. J. 1981. "Radar and Raingauge Observations of Orographic Rain Over South Wales," *Quarterly Journal of the Royal Meteorological Society*, Vol 107, pp 643-670.

Huff, F. A. 1955. "Comparison Between Standard and Small Orifice Raingages," *Transactions of the American Geophysical Union*, Vol 36, pp 689-694.

_____. 1970. "Sampling Errors in Measurement of Mean Precipitation," *Journal of Applied Meteorology*, Vol 9, No. 1, pp 35-44.

_____. 1971. "Evaluation of Precipitation Records in Weather Modification Experiments," *Advances in Geophysics*, Academic Press, New York, Vol 15, pp 59-134.

Huff, F. A., and Changnon, S. A., Jr. 1977. "A Hydrometeorological Research Program," *Water Resources Bulletin*, Vol 13, No. 3, pp 574-581.

Huff, F. A., and Towery, N. G. 1978. "Utilization of Radar in Operation of Urban Hydrologic Systems," *Preprints: Eighteenth Conference on Radar Meteorology, American Meteorological Society, 28-31 March 1978, Atlanta, GA*, pp 437-441.

Huff, F. A., Changnon, S. A., and Vogel, J. L. 1980. "Convective Rain Monitoring and Forecasting System for an Urban Area," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL*, pp 56-61.

Joss, J. K., and Gori, E. G. 1978. "Shapes of Raindrop Size Distributions," *Journal of Applied Meteorology*, Vol 17, No. 7, pp 1054-1061.

Kinzer, G. D., and Gunn, R. 1951. "The Evaporation, Temperature, and Thermal Relaxation Time of Freely Falling Waterdrops," *Journal of Meteorology, American Meteorological Society*, Vol 8, No. 1, pp 71-82.

Larson, L. W., 1971. *Precipitation and Its Measurement, a State of the Art*, Water Resources Series 24, Water Resources Research Institute, University of Wyoming, Laramie, WY, p 74.

Larson, L. W., and Peck, E. L. 1974. "Accuracy of Precipitation Measurements for Hydrologic Modeling," *Water Resources Research*, American Geophysical Union, Vol 10, No. 4, pp 857-863.

Linsley, R. K., and Kohler, M. A. 1951. "Variations in Storm Rainfall Over Small Areas," *Transactions of the American Geophysical Union*, Vol 32, pp 245-250.

Marshall, J. S., and Palmer, W. M. 1948. "The Distribution of Raindrops with Size," *Journal of Meteorology*, Vol 5, No. 1, pp 165-166.

Martner, B. E. 1975. Final Report on the University of Wyoming's Participation in NSSL Project Storm Intercept. Department of Atmospheric Science, University of Wyoming, Laramie, WY, p 14.

Miers, Bruce T., and Huebner, George L. 1985. "Feasibility of Utilizing Satellite and Radar Data in Hydrologic Forecasting," MP EL-79-6, Report 8 (Military Hydrology Series), US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Saffle, R. E. 1976. "D/RADEX Products and Field Operations," *Preprints: Seventeenth Conference on Radar Meteorology, American Meteorological Society, 26-29 October, 1976, Seattle, WA*, pp 555-559.

Seliga, T. A., and Bringi, V. N. 1976. "Potential Use of Radar Differential Reflectivity Measurements at Orthogonal Polarizatons for Measuring Precipitation," *Journal of Applied Meteorology*, Vol 15, No. 1, pp 69-76.

_____. 1978. "Preliminary Results of Differential Reflectivity Measurements in Rain," *Preprints: Eighteenth Conference on Radar Meteorology, American Meteorological Society, 28-31 March 1978, Atlanta, GA*, pp 134-138.

Spilhaus, A. F. 1948. "Drop Size, Intensity and Radar Echo of Rain," *Journal of Applied Meteorology*, Vol 5, pp 161-164.

Stout, G. E., and Mueller, E. A. 1968. "Survey of Relationships Between Rainfall Rate and Radar Reflectivity in the Measurement of Precipitation," *Journal of Applied Meteorology*, Vol 7, No. 6, pp 465-474.

Twomey, S., 1953. "On the Measurement of Precipitation Intensity by Radar," *Journal of Meteorology*, Vol 10, No. 1, pp 66-67.

Ulbrich, C. W., and Atlas, D. 1975. "The Use of Radar Reflectivity and Microwave Attenuation to Obtain Improved Measurements of Precipitation Parameters," *Preprints: Sixteenth Conference on Radar Meteorology, American Meteorological Society, 22-24 April 1975 Houston, TX*, pp 496-503.

Wilson, J. W. 1970. "The Integration of Radar and Raingage Data for Improved Rainfall Measurement," *Journal of Applied Meteorology*, Vol 9, No. 3, pp 489-497.

Wilson, J. W., and Brandes, E. A. 1979. "Radar Measurement of Rainfall — A Summary," *Bulletin of the American Meteorological Society*, Vol 60, No. 9, pp 1048-1058.

Winston, H. A., and Ruthi, L. J. 1986. "Evaluation of RADAP II Severe-Storm-Detection Algorithms," *Bulletin of the American Meteorological Society*, Vol 67, No. 2, pp 145-150.

Woodley, W. L., and Herndon, A. 1970. "A Raingage Evaluation of the Miami Reflectivity-Rainfall Rate Relation," *Journal of Applied Meteorology*, Vol 9, No. 4, pp 258-264.

Woodley, W. L., Olsen, A. R., Herndon, A., and Wiggert, V. 1975. "Comparison of Gage and Radar Methods of Convective Rain Measurement," *Journal of Applied Meteorology*, Vol 14, No. 8, pp 909-928.

World Meteorological Organization. 1973. *Annotated Bibliography on Precipitation Measurement Instruments*, Report 17, WMO-343, Geneva, p 278.

APPENDIX A: ANNOTATED BIBLIOGRAPHY OF RADAR-RAIN GAGE RELATIONS

Introduction

This annotated bibliography is a compilation of references pertinent to the subject of radar-rain gage relations. References are included on specific meteorological projects such as the Florida Area Cumulus Experiment (FACE), the Garp Atlantic Tropical Experiment (GATE) and High Plains Experiment (HIPLEX). Brief reviews of the work being done in radar meteorology in other countries are also included. Several references were taken from the following documents:

> Brandes, E. A., and Wilson, J. W. 1982. "Measuring Storm Rainfall by Radar and Rain Gage," *Thunderstorms: A Social Scientific, and Technological Documentary. Instruments and Techniques for Thunderstorm Observation and Analysis, Vol 3*, National Oceanic and Atmospheric Administration, Silver Spring, MD, pp 242-272.

and

> Wilson, J. W., and Brandes, E. A. 1979. "Radar Measurement of Rainfall—A Summary," *Bulletin of the American Meteorological Society*, Vol 60, No. 9, pp 1048-1058.

Bibliography

1. Anderl, B., Attmannspacher, W., and Schultz, G. A. 1976. "Accuracy of Reservoir Inflow Forecasts Based on Radar Rainfall Measurements," *Water Resources Research*, Vol 12, No. 2, pp 217-223.

   For efficient application of optimum operation procedures to flood protection reservoirs it is essential to forecast the relevant inflow hydrographs on-line, i.e., during a storm. This can be achieved with the aid of a weather radar linked to a computer in which the optimum reservoir operating program is stored as well as a program of a hydrologic rainfall-runoff model producing the reservoir inflow hydrographs from radar-measured rainfall data. These inflow hydrographs may be evaluated on the computer during each storm event and can be updated every 5 min if necessary. The accuracy of these computed hydrographs was tested against the recordings of two river gages installed in catchments close to a weather radar at Hohenpeissenberg in Upper Bavaria. By using a linearly distributed mathematical catchment model it was shown that for the two rivers the synthetic hydrographs computed from radar-measured rainfall were more accurate than those obtained from continuous measurements of the official point rain gage network of the German Weather Service (one recording gage in 500 km^2) and that they were of the same accuracy as those obtained from a special very dense rain gage network (one recording gage in 25 km^2) set up for research purposes in the same area. (Author's abstract)

2. Antonio, M. A. 1984. "Radar and Raingage Precipitation Comparison as a Function of the Integration Time," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland*, pp 589-593.

The aim of this work was to show the dependence of the Z-R relationship on the area and, mainly, on the integration time performed over the basic radar data. Such dependence can be verified on the results presented here, in spite of the fact that only one month's data - February, 1982 - is dealt with, which limited the availability of a large number of simultaneous radar and raingage data sets.

The increase in the integration area of the radar data, even for short time intervals, smooths the gradients and hides possible errors resulting from the antenna pointing and for the gage locations. Further studies will be also developed in a next phase for other gages, areas, and integration times using longer data records - January-March, 1982; the effect of gage location - range dependence - will be also analysed. (Author's summary)

3. Austin, G. L., and Ahn, Y. D. 1972. "Vertical Motion of Patterns in Radar Records of Showers," *Journal of Applied Meteorology*, Vol 12, No. 2, pp 354-358.

A technique is described for finding an "effective pattern fallspeed" from arrays of radar data taken at different heights. A weather radar whose antenna scans in three dimensions at many elevation angles inevitably takes a few minutes to record the three-dimensional structure of precipitation patterns. The effective pattern fallspeed allows this rather coarse sampling time to be improved and enables the precipitation pattern to be extrapolated to the ground with the time resolution improved by a factor of about 5 to 1 min. Comparing the distance moved by a storm in this time with the spatial resolution of the radar suggests that this is close to the upper limit of useful time resolution. (Author's abstract)

4. Austin, G. L., and Austin, L. B. 1974. "The Use of Radar in Urban Hydrology," *Journal of Hydrology*, Vol 22, No. 1, pp 131-142.

The radar and raingauge records of summer storms occurring over the city of Ottawa between 1969 and 1972 were used to study events which lead to the flooding of house basements. It was found that these tended to occur as a result of slow moving storms and on one occasion due to a storm elongated in its direction of travel. These features of storm dynamics appeared to be more important than either the intensity of the storm (maximum instantaneous rainfall rate) or the total accumulation. A brief discussion of the match between the scale of resolution of the radar and the watershed scale size in urban areas is included. (Author's abstract)

5. Austin, P. M. 1969. "Application of Radar to Measurement of Surface Precipitation," Technical Report ECOM-0319-F, US Army Electronics Command, Fort Monmouth, NJ, p 93.

This report contains two major sections. In the first, consideration is given to the accuracy and practicality of measuring surface precipitation by radar. The second summarizes studies which have been made regarding mesoscale precipitation patterns and their relation to larger-scale circulations.

The radars which are in operation at the Weather Radar Laboratory and M.I.T. and auxiliary instrumentation for quantitative measurements are described, and the requirements for adequate radar calibration are discussed. Also included are estimates of the overall accuracy for the equipment and techniques which are employed. A data processor for printing digital maps or presenting data in other directly applicable form is described.

A number of raindrop-size measurements and the information they provide concerning Z-R relations appropriate for New England storms are summarized. Measurements of reflectivity in hailstorms and snowstorms are also discussed.

It is concluded that for convective storms a properly instrumented 10-cm radar can provide more accurate measurements of rainfall over an area than can a network of gauges. A wavelength as short as 3 cm is shown to be unsatisfactory for measuring precipitation because of attenuation.

In widespread storms, appreciable errors (occasionally a factor of two or three) may result from differences between the precipitation in the volume sampled by the radar and that reaching the surface. Observations of such effects are presented and discussed.

Advantages and liabilities both of the radar and of a network of gauges for measuring precipitation over an area are illustrated by experiments in which simultaneous measurements by the two methods are compared.

Techniques have been developed for deducing the small-scale atmospheric motions from radar and rain-gauge data. Resulting contributions to the energetics and dynamics of larger-scale systems through release of latent heat and vertical transport of quantities such as sensible heat and momentum can be computed. In the analysis of a selected cyclonic storm it was found that the effects of small-scale convection were comparable in magnitude to those of the synoptic-scale circulations. (Author's summary)

6. Austin, P., and Houze, R. A. 1972. "Analysis of the Structure of Precipitation Patterns in New England," *Journal of Applied Meteorology*, Vol 11, No. 6, pp 929-935.

The studies presented here were undertaken to provide a specific and quantitative description of the precipitation patterns in New England storms. Basic data were quantitative radar observations and detailed raingage records.

Nine storms covering a wide range of synoptic and seasonal situations were subjected to systematic analysis. Also the general shape and configuration of the mesoscale rain areas in 17 fully developed cyclones were observed.

The precipitation patterns, which at first glance appeared very dissimilar, turned out to be composed of subsynoptic-scale precipitation areas with rather clearly definable characteristics and behavior. Four distinct scales of precipitation areas have been recognized and described: synoptic areas which are larger than 10^4 km^2 and have a lifetime of one or several days; large mesoscale areas which range from 10^3 to 10^4 km^2 and last several hours; small mesoscale areas which cover 100 to 400 km^2 and last about an hour; and cells which are roughly 10 km^2 and often last only a few minutes, rarely as long as half an hour. In the cases which were analyzed every precipitation area of any of these scales contained one or several of each of the smaller sized precipitation areas. The motions and relative intensities of precipitation areas of the various scales also show a consistent pattern. The vertical location and depth of the layer containing cells varied greatly from one storm to another but remained about the same within any particular storm.

The consistent occurrence of subsynoptic-scale rain areas with similar characteristics and behavior in a variety of precipitation patterns provides a means for describing the distribution of precipitation in any storm in a parameterized manner and also permits realistic modeling of storms for meteorological and hydrological studies. (Author's abstract)

7. Austin, P. M. 1980. "Some Comparisons of Rainfall Amounts Measured by Radar and With Rain Gauges," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL*, pp 431-437.

This paper presents the preliminary results of an investigation of various factors that can contribute to the discrepancies between radar-indicated rainfall amounts and those measured with rain gages. Emphasis is on the Z-R relationship, vertical variation in reflectivity, horizontal variations in rainfall, sensitivity of the radar, and the time interval between radar maps. The comparisons presented herein illustrate qualitatively various pertinent factors and point up the desirability of making more comprehensive physical analyses before attempting to develop objective techniques for adjusting radars by real-time comparisons of gauge and radar indications at a few selected points.

8. Austin, P. M. 1981. "On Deducing Rainfall from Radar Reflectivity Measurements," *Preprints: Twentieth Conference on Radar Meteorology, American Meteorological Society, 30 Nov-3 Dec 1981, Boston, MA*, pp 200-207.

In this study, grouping of the storms was based primarily on Z_e-R_e relations deduced from radar-gauge comparisons. However, a tendency was noted for storms in each group to exhibit characteristic precipitation patterns and ranges of reflectivity values. Thus, reflectivity measurements can provide guidelines for determining into which group a given storm should be placed, what Z_e-R_e relation is appropriate, and what adjustments should be made for the effects of other factors. It is emphasized that the indications are guidelines, not definition criteria. Therefore, it is not practical at this time to attempt fully automated radar measurements of rainfall. A knowledgeable meteorologist or hydrologist is needed to make judgmental decisions. (Author's summary)

9. Austin, P. M. 1987. "Relation Between Measured Radar Reflectivity and Surface Rainfall," *Monthly Weather Review*, Vol 115, No. 5, pp 1053-1071.

A number of physical factors that influence the relation between measured radar reflectivity and surface rainfall are considered both theoretically and through detailed comparisons of radar and raingauge measurements. These factors include natural differences in raindrop-size distribution, enhancement of radar reflectivity by presence of hailstones or melting snow, diminution of reflectivity by downdrafts, and low-level changes in rainfall rate caused by accretion or evaporation. Results of 374 comparisons in 20 storms, which cover a wide variety of synoptic situations and rainfall patterns, are presented. Magnitudes of the effects of the different factors are estimated, and storm types where they are likely to be significant are pointed out. Also, some ways of compensating for the observed effects are suggested. (Author's abstract)

10. Barnston, A. G., and Thomas, J. L. 1983. "Rainfall Measurement Accuracy in FACE: A Comparison of Gage and Radar Rainfalls," *Journal of Climate and Applied Meteorology*, Vol 22, No. 12, pp 2038-2052.

The agreement of radar with raingage rainfall measurements during the second phase of the Florida Area Cumulus Experiment (FACE-2) is examined. FACE-2 rainfall was measured in a 1.3×10^4 km^2 target area using 111 nearly uniformly distributed gages at an average density of 117 km^2 per gage and using a WSR-57 radar adjusted daily with a dense raingage network distributed over 500 km^2. The radar-versus-gage agreement is studied in order to evaluate the accuracy of the unadjusted radar measurements and the effectiveness of the adjustment technique in improving the radar measurements. Implicit in the comparison is an assumption that the gage rainfalls are the relative standard of accuracy.

Before gage adjustment of the radar rainfalls, mean differences between radar and gage target area rainfalls are slightly positive (radar~$1.10 \times$ gage) on dry days but become considerably negative (radar~ $0.70 \times$ gage) on wet days. Following gage adjustment, the mean gage agreement generally is much improved. However, the day-to-day variation of the differences is not diminished after the adjustment. This is attributed to misrepresentations of the gage-to-radar rainfall ratio in the dense raingage network which are caused by the spatial variation of that ratio within the overall target area. (Author's abstract)

11. Battan, L. J. 1973. *Radar Observation of the Atmosphere*, University of Chicago Press, Chicago, IL, p 324.

This book is a comprehensive review of the current state of the art concerning weather radar. It includes specific chapters on a wide range of topics including the principles of radar, attenuation of the radar signal, use of radar for precipita-

tion measurement, and radar observations of medium- and large-scale systems. The book includes an extensive, up-to-date bibliography.

12. Bellon, A. 1981. "Geographical Distribution of Radar Echoes, Growth and Decay," *Preprints: Twentieth Conference on Radar Meteorology, American Meteorological Society, 30 Nov -3 Dec 1981, Boston, MA*, pp 170-173.

It is the belief of the author that the assimilation of preferred behavior of rain patterns, which enables a forecasting technique to depart from the "status quo" assumption, based on a statistical map of average tendencies, would improve the accuracy of the forecasts only slightly in the Montreal region. In addition, the absence of contrasting land and water bodies in this region reduces the truly orographic effects observed in other parts of the world, like south Wales in Britain, where the enhancement of a precipitation system is of significant proportions and the non-inclusion of orography would constitute a useless forecast product. (Author's summary)

13. Blackmer, R. H., Jr., Duda, R. O., and Reboh, R. 1973. "Application of Pattern Recognition Techniques to Digitized Weather Radar Data," SRI Project 1287 Final Report for Techniques Development Laboratory, System Development Office, National Weather Service/NOAA, Menlo Park, CA.

This paper describes the techniques for echo tracking on a digitized weather radar. Algorithms are included.

14. Brady, P. J., Schroeder, M. J., and Poellot, M. R. 1978. "Automatic Identification and Tracking of Radar Echoes in HIPLEX," *Preprints: Eighteenth Conference on Radar Meteorology, American Meteorological Society, 28-31 March 1978, Atlanta, GA*, pp 139-143.

The automatic cell tracking (ACT) algorithms are being used to process the data from one Kansas and two Montana radar systems used in HIPLEX. The algorithms are not perfect, and a careful hand analysis by an experienced meteorologist would likely produce a more intuitively correct tracking report. However, when over 1200 digital radar tapes have to be processed some months before the beginning of each following field season, hand analysis is simply not practical nor is it cost-effective. The ACT algorithms have processed the digital radar data from 1977 which will be used in planning for the 1978 HIPLEX field season, and the 1978 data will be used in planning the 1979 season, etc. Another big advantage of the ACT algorithms is that they are consistent and they are objective, and this will be reflected in the statistics produced from these programs. The algorithms developed at the University of North Dakota will permit the HIPLEX research groups the ability to analyze the radar data on a timely basis, a luxury not afforded to many research groups in the past. (Author's summary)

15. Brandes, E. A. 1974. "Radar Rainfall Pattern Optimizing Technique," NOAA Technical Memorandum ERL NSSL-67, Norman, OK.

Estimates of precipitation are improved when quantitative radar data are combined with rain gage observations. Gage observations are used to calibrate radar data as well as to estimate precipitation in areas without radar data. Error estimates of areal precipitation depth for five cases of widespread rainfalls over a 1,000-nautical-sq-mile* watershed, averaged 8 to 15 percent with densities of one gage per 270 and 675 nautical sq miles, respectively. Precipitation estimates derived from an objective analysis of rainfall depths observed at the calibration gages alone produced errors of 10 and 21 percent. Radar data added to gage observations increased the explained variance at test gages, beyond that given by gage data alone, from 66 to 72 percent and 50 to 59 percent for the same calibrating gage. Large storm-to-storm variations in average radar calibration and large spatial correction variations within storms were attributed to propagation effects. (Author's abstract)

16. Brandes, E. A. 1975. "Optimizing Rainfall Estimates with the Aid of Radar," *Journal of Applied Meteorology*, Vol 14, No. 11, pp 1339-1345.

    Estimates of precipitation are improved when raingage observations are used to calibrate quantitative radar data as well as to estimate precipitation in areas without radar data.

    Estimated areal precipitation depth errors for nine rainfalls over a 3,000-km^2 watershed averaged 13 and 14 percent (1.5 and 1.8 mm) when the radar was calibrated by networks of rain gages having densities of one gage per 900 and 1,600 km^2. Areal precipitation estimates derived from rainfalls observed at the gages alone produced errors of 21 and 24 percent (2.5 and 3.0 mm). Adjusting the radar data by a single calibration factor (the simple average ratio of gage-observed and radar-inferred rainfall at all input gages without regard to the spatial variation among ratios) resulted in error reduction to 18 percent (2.1 mm). Radar data added to gage observations also increased the explained variance in point rainfall estimates above that from gages alone, from 53 to 77 percent and 46 to 72 percent for the above gage densities. (Author's abstract)

17. Brandes, E. A., and Sirmans, D. 1976. "Convective Rainfall Estimation by Radar: Experimental Results and Proposed Operational Analysis Technique," *Preprints: Conference on Hydrometeorology, American Meteorological Society, 20-22 April 1976, Forth Worth, TX*, pp 54-59.

    Comparisons between radar-inferred and gage-observed rainfalls show mean storm differences exceeding a factor of 2. Within-storm, radar-estimated, standard errors (exclusive of bias) averaged 30 percent and revealed a tendency to overestimate light rainfalls and underestimate heavy rainfalls. A technique has been described whereby a distribution of gages can be used to correct bias and spatial errors inherent in radar rainfall estimates.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3 of the main text.

18. Brandes, E. A., and Wilson, J. W. 1982. "Measuring Storm Rainfall by Radar and Rain Gage," *Thunderstorms: A Social, Scientific and Technological Documentary. Instruments and Techniques for Thunderstorm Observation and Analysis*, Vol 3, National Oceanic and Atmospheric Administration, Norman, OK, pp 241-272.

This chapter is an excellent review of the state of the art of measuring rainfall by radar and rain gage. Subjects covered include gage measurement of rainfall, instrument errors, areal estimate errors, radar measurement of rainfall, estimates of radar reflectivity, advantages and disadvantages of time and space averaging of radar measurements and variations in the Z-R relationship. There are extended sections dealing with radar-gage comparisons and ways to adjust radar-derived rainfall estimates. An excellent bibliography concludes the chapter.

19. Burgess, M. D., and Hanson, C. L. 1983. "Microprocessor-Controlled Precipitation Data Collection System," *Journal of Hydrology*, Elsevier Science Publishers B.V., Amsterdam, the Netherlands, Vol 66, pp 369-374.

A microprocessor system was developed that utilizes a removable memory module for precipitation gage data storage and retrieval. The system can be used in remote locations because the circuitry draws little power. Precipitation data are entered directly from the removable memory module into a computer for data storage and analysis. This eliminates recorder charts and manual data entry into a computer system.

20. Calheiros, R. V., and Zawadzki, I. 1981. "Statistically Derived Z-R Relationship for Hydrology," *Preprints: Twentieth Conference on Radar Meteorology, American Meteorological Society, 30 Nov - 3 Dec 1981, Boston, MA*, pp 81-84.

The method presented here permits the use of past gate and radar records (not necessarily simultaneous) for the determination of a Z-R relationship. If the radar is located in an orographically uniform region, one can assume a uniform climatology of precipitation. Thus a single rain gage is sufficient to study the range effect on hydrological measurements by radar and to extend the useful radar range beyond the presently accepted distance. If data from a number of rain gages are available, the Z-R relationship can be stratified by storm type or by the measured rain parameters such as mean rain rate. Seasonal variations in the Z-R relationship can also be studied from past records.

The statistically derived Z-R relationship can reveal a non-linear (in log coordinates) behavior difficult to detect in scattergrams of simultaneous radar-raingage measurements.

Applying this method requires a careful record of radar operation. Radar records chosen at random are analyzed to obtain the probability of kZ; absolute probabilities must reflect, for every hour, whether the absence of echo is due to radar failures or actual absence of rain. In the present work available statistics were used and these were obtained without the care necessary for our purpose. Thus, although qualitatively the results presented here are correct, the exact values of b and its range dependency are to be taken with some reserve. (Author's summary)

21. Cavalli, R. 1984. "The Operational Swiss Weather Radar Information Distribution Network," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland,* pp 21-24.

Since 1979, the information of the two weather radars of the Swiss Meteorological Institute (SMI) has been distributed in digital form over leased telephone lines. The most important of the total of some 15 users are the forecasting centers of Zurich, Geneva airport, Kloten airport, and Locarno-Monti of the SMI. During the first years of operation, the users received the digitized radar data directly from the radar sites. By alternating the transmission of the two radars, a single telephone line could be used for both images.

Within the framework of a project called DISAT, the radar distribution network has been extended, in order to disseminate the radar images post-processed under DISAT. The main purpose of DISAT is to establish and operate real-time processing and distribution of information from meteorological satellites and radar and from automatic weather stations. The DISAT computer,a VAX 11/780 located at Locarno-Monti, combines the pictures produced locally by the two radars to a smoothed composite picture. With a minimal delay, because of the post-processing, the composite picture is sent across the already existing network of DISAT, which otherwise is dedicated to the distribution of satellite pictures. In case of a breakdown of the DISAT computer, transmission automatically falls back to the original frames from the two radar sites.

Besides its real-time tasks, the DISAT computer is used for monitoring the radar calibration and for research. (Author's summary)

22. Clarke, S., Seliga, T. A., and Aydin, K. 1983. "Estimates of Rainfall Rate Using the Differential Reflectivity (Z_{DR}) Radar Technique: Comparisons with a Raingage Network and Z-R Relationships," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada,* pp 479-484.

In the autumn of 1981 the CHILL radar was operated with a dense network of 25 rain gages in a research program in central Illinois to compare radar-derived estimates of rainfall rates with gage values. The primary goal of the experiments was to obtain data for testing the differential reflectivity (Z_{DR}) radar technique of measuring rainfall. This paper presents the results of an event on November 23 when one of the longest lasting and most intense rainfalls of the observational period occurred.

The first quantitative comparisons of rainfall rates between radar-Z_{DR} derived values (R_{ZDR}) and rain gages (R_G) were performed by Seliga et al. (1981) using the slow-switching CHILL radar and the Chicago Hydrometeorological Area

Project's (CHAP) raingage network. The Z_{DR} estimates were very encouraging and compared more favorably with raingage values than results from two Z-R relationships (R_{ZR}), one of which was calibrated with 20 min of raingage-radar data. For example, (R_{ZDR}) was nearly equal to (RG), and the relative absolute average difference between R_{ZR} and R_G samples was about one half the difference obtained using the differences between R_{ZR} and R_G . Other encouraging rainfall comparisons using the Z_{DR} technique were obtained with ground-based disdrometers by Bringi et al. (1982) and Goddard et al. (1982). (Author's summary)

23. Cole, J. A. 1977. "Online Flow Forecasting for the River Dee, 1976 - An Audio-Visual Explanation," *Preprints: Modeling in Hydrologic Processes, Proceedings of the Fort Collins Third International Hydrology Symposium on Theoretical and Applied Hydrology, 27-29 July 1977, Fort Collins, CO,* Water Resources Publications, Fort Collins, CO, pp 333-343.

    Flow forecasting on the Welsh Dee is based on an extensive telemetry network. This transmits water levels in four reservoirs and river discharge from nine tributaries and at six stations on the Dee itself. Rainfall data are received both from conventional rain gauges and from a weather radar.

    The forecasting of flows is done on-line on a small computer (64-k store). Tributary responses are derived from a version of Lambert's "ISO" model. Flows entering the Dee are then routed downstream by application of Price's variable parameter diffusion model.

    A sequence of 70 photographs and diagrams, accompanied by spoken commentary, details the Dee telemetry and flow-forecasting system and shows examples of the results obtained during the first year of operation. (Author's abstract)

24. Collier, C. G., Harrold, T. W., and Nicholass, C. A. 1975. "A Comparison of Areal Rainfall as Measured by a Raingauge Calibrated Radar System and Raingauge Networks of Various Densities," *Preprints: Sixteenth Conference on Radar Meteorology, American Meteorological Society, 22-24 April 1975, Houston, TX,* pp 467-472.

    In order to examine the effectiveness of a rain gauge-calibrated radar system, it is necessary to compare in some detail the accuracy of measurements of areal rainfall made by a radar-calibrated rain-gauge network using various densities of rain gauges, with rainfall measurements obtained solely using rain gauge networks of various densities. Such a study must be made in a variety of synoptic weather types.

    The present study has shown that the accuracy of radar measurements of rainfall over sub-catchments distant from a calibration rain gauge site may be improved by using additional calibration sites, and that when the radar beam intersects the melting layer, the accuracy achieved in the measurements of hourly rainfall was reduced by about 10%.

It has been shown that a radar calibrated at two sites can be used to estimate areal rainfall over sub-catchments with the same accuracy as a network of about 10 rain gauges over 1,000 km^2 in widespread uniform rain, provided that the radar beam does not intersect the melting layer, and that the calibrated radar is as accurate as about 50 gauges per 1,000 km^2 in showery conditions.

The calibrated radar system may be used to make accurate measurements of areal rainfall over areas considerably larger than the 1,000-km^2 area discussed in this paper. Such measurements are unlikely to be a viable prospect using a network of rain gauges. (Author's summary)

25. Collier, C. G., and Larke, P. R. 1978. "A Case Study of the Measurement of Snowfall by Radar: An Assessment of Accuracy," *Quarterly Journal of the Royal Meteorological Society*, Vol 104, pp 615-621.

    Radar measurements during a period of snowfall in a region of variable terrain are described. The accuracy of estimates of areal snow depth, using a calibrated radar, is shown to be similar to that achieved for areal rainfall using the same technique. This detailed case study supports similar conclusions made by other workers, who used more cases, but fewer validating measurements. It is also shown that, provided the variations in terrain height are not very large, compensation for the effects of melting over low terrain can be made in deriving the snow depth field by using two independent snow depth calibration measurements-one representative of upland areas, and the other of lowland areas. (Author's abstract)

26. Collier, C. G., Larke, P. R., and May, B. R. 1983. "A Weather Radar Correction Procedure for Real-Time Estimation of Surface Rainfall," *Quarterly Journal of the Royal Meteorological Society*, Vol 109, pp 589-608.

    Several sources of error have been identified in measuring rainfall by radar. In this paper these sources of error are discussed as they affect the calibration of a radar system using raingauge data. Present calibration techniques are considered, and the need for procedures based upon a knowledge of the structure of precipitation systems is noted. Finally, a new procedure is described, and its performance assessed for a number of cases of frontal and convective rainfall. (Author's abstract)

27. Collier, C. G. 1984. "Radar Meteorology in the United Kingdom," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 1-8.

    Radar technology has been used extensively in meteorology ever since it first became available some 40 years ago. In the United Kingdom, as in many other countries, there is an ongoing research and operational program aimed at extending the use of the technology to investigate and predict atmospheric phenomena. Current and past work is summarized in this paper, and likely future developments, based upon extensions of current plans, are considered. (Author's summary)

28. Collier, C. G. 1984. "The Operational Performance in Estimating Surface Rainfall of a Raingauge-Calibrated Radar System," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 257-262.

A raingauge calibration procedure has been successfully introduced into an unmanned radar system operating fully automatically. Calibrated radar data are provided in real time to both meteorological and hydrological users. The accuracy of these data has been assessed by comparison with raingauge measurements and found to be comparable to the accuracy attained in the Dee Weather Radar Project. The calibration procedure has been found to improve the overall accuracy of the uncalibrated data within about 75 km of the radar site in frontal rainfall even when bright-band effects are present. Convective rainfall calibration has a smaller effect, on average, although it may have a large effect in individual cases. Problems encountered with the real-time operation have been highlighted, and ways of minimizing the detrimental effects on the accuracy of measurement of such problems have been discussed. (Author's summary).

29. Crane, R. K. 1975. "Comparison Between Reflectivity Statistics at Heights of 3 and 6 Km and Rain Rate Statistics at Ground Level," *Preprints: 16th Radar Meteorology Conference, American Meteorological Society, 22-24 April 1975, Houston, TX*, pp 479-483.

Rain scatter and surface rain rate data were obtained from October 3, 1970, to October 2, 1971, using a bistatic radar system and tipping bucket rain gauges located in southeastern Virginia. The bistatic radar system was operated at 3.7 GHz and provided continuous surveillance of small volumes with maximum linear dimensions less than 3.0 km at both the 3-km and 6-km heights. One-minute averages of the scattering cross section per unit volume values, Z_e, were used to produce empirical density functions of Z_e for each height. The rain gauge data were used to estimate 1-min rain rate averages. The rain rate averages were used to estimate the scattering cross section per unit volume, Z, using a $Z = 270R^{1.3}$ relationship. Empirical density functions were generated for Z for each of the rain gauges.

The empirical density functions for Z_e observed at the 3-and 6-km heights and Z observed at the surface were different. The density functions for Z_e at 3 km and Z at the surface were identical only for summer thundershowers. The density functions for Z_e at 6 km and Z at the surface were different for all observed rain types.

The results of the experiment show that the distribution functions for reflectivity may significantly change at heights below the level of the melting layer. The results could be interpreted as indicative of a change in the Z-R relationship since the distribution functions were identical for showery rain and different for widespread rain. This interpretation is not correct because the Z_e value threshold set by the effect of sidelobes and a finite scattering volume restricts the comparison to high Z levels (greater than 42 db). The drop size distributions reported by Mueller and Sims do not show a significant dependence upon rain types for reflectivity levels above 40 dBZ. The drop size data further show that at the higher rain rate values associated with high reflectivity values, the spread in Z values for a fixed rain rate is smaller than for lower rain rate values. Finally, the gauge-data-generated Z values are consistently 7 db larger than the observed Z_e values for all probabilities of occurrence corresponding to Z values above 42 dBZ. The observed change in the distribution functions of reflectivity with height suggest that care should be exercised in calibrating weather radar systems using surface rain gauge observations. (Author's summary)

30. Crawford, K. C. 1977. "The Design of a Multivariate Mesoscale Field," Ph.D. Dissertation, The University of Oklahoma, Norman, OK, p 155.

    Radar reflectivities and rain gage data can be combined in many ways to estimate convective-storm surface rainfall. However, optimum (interpolation-produced) estimates used to evaluate modification experiments or to implement sampling techniques require that statistical properties of such estimates be known. Such properties derive from the storm structure, implied by the observed data, and are deduced by using space-time covariance and cross-covariance functions. A four-dimensional Gaussian-damped function can reflect relevant characteristics (physical and statistical) of southeastern Montana convective systems. Functional parameter values relate to system features of size, motion-speed, and preferred storm track. An average southeast Montana system compares and contrasts with the features of an Oklahoma counterpart.

    The optimum interpolation methodology is enhanced to account for multivariate means and variances. Bivariate analyses that use radar/rain-gage data sets are shown superior to the best univariate results. The analyses reflect patterns derived from radar rainfall estimates and scaled to rain gage magnitudes. The influence of a Z-R relationship on analysis accuracy is minimal, and the model's signal recoverability qualities are shown. Consequences of filtering data set observations improperly are discussed.

    The development of an experimental design evaluation function is completed through modelling the parameter means and variances. Predictand-related sensors are shown essential to network design. Tradeoffs in multivariate sensor deployments (spatial and temporal) are explained. Deployment along and across a preferred storm track is related to covariance, anisotropy, gage density, temporal sampling intervals, the availability of radar data, and the interrelationships among the multivariate predictor data sets. Moreover, optimal sensor orientation to sample a moving convective system is found best to observe the system's accumulated rainfall pattern. (Author's abstract)

31. Curry, R. G. 1970. "A Study of the Applicability of Weather Radar in Streamflow Forecasting," Texas A&M Research Foundation, College Station, TX, DA Project No. 1TO.14501.B81A.00.00, p 49.

Streamflow routing techniques are applied for hydrograph synthesis to the 234 mi^2 East Yegua Creek basin in central Texas. Digitized data for a grid size of 5 by 5 miles are obtained from a 10.3 cm radar and are utilized in the estimation of rainfall over the basin. These data are compared with rainfall measured by 27 recording and non-recording gages spaced uniformly over the basin. Hydrographs have been synthesized for four flood events based on radar-estimated and actually observed rainfall. The results, when compared with the observed hydrographs, are encouraging. The routing coefficients, however, vary considerably with antecedent soil-moisture conditions, rainfall intensity, and time of the year.

The primary difficulty in the use of radar-estimated rainfall was that rainfall intensities were underestimated rather severely. The spatial variability of the rainfall was good and revealed the capability of radar to measure mesoscale variations of rainfall in a "real-time" sense. (Author's abstract)

32. Damant, C., Austin, G. L., Bellon, A., and Broughton, R. S. 1983. "Errors in the Thiessen Technique for Estimating Areal Rain Amounts Using Weather Radar Data," *Journal of Hydrology*, Vol 62, pp 81-94.

    High-resolution radar data were used to estimate rainfall accumulation patterns for 13 summer storms. The Thiessen polygon method is used to estimate average rainfall over the Yamaska Basin. Thiessen estimates were compared to estimated radar rainfall averages over the basin. Errors for the 13 storms analyzed gave values between 3 and 69 percent for the whole basin. (Author's abstract)

33. Dennis, A. S., Koscielski, A., Cain, D. E., Hirsch, J. H., and Smith, P. L., Jr. 1975. "Analysis of Radar Observations of a Randomized Cloud Seeding Experiment," *Journal of Applied Meteorology*, Vol 14, No. 5, pp 897-908.

    Magnetic tape records for radar observations of 80 moving 1-hour test cases in a three-way randomized (no-seed, salt, silver iodide) cloud seeding experiment have been analyzed in terms of echoing areas and radar-estimated rainfall amounts. Individual test cases ranged from non-precipitating cumulus up to moderate thunderstorms with echoing areas exceeding 100 km^2 and rainfall estimated at 3,000 kT in 1 hr.

    Out of numerous predictor variables, cloud depth is found to be the best single predictor for both echoing area and radar- estimated rainfall. The echoing area and radar-estimated rainfall are very closely correlated. A cube-root transformation of the radar-estimated rainfall improves the correlation between cloud depth and the radar-estimated rainfall for the no-seed (control) sample to 0.91. For clouds of a given depth, both the echoing area and radar-estimated rainfall are larger in seeded than in unseeded cases. The differences between no-seed and silver iodide cases are significant at the 1 percent level. The indicated effects, expressed as a percentage of the echoing area or radar-estimated rainfall in the no-seed cases, decrease with cloud depth.

A comparison of no-seed and AgI cases with the aid of a one-dimensional steady-state cloud model shows that AgI seeding may have led to increases in maximum cloud height averaging 600 m.

It is concluded that seeding affected the precipitation in the Cloud Catcher test cases through both the microphysical processes and the cloud dynamics. (Author's abstract)

34. Dimaksyan, A. M., and Zotimov, N. V. 1965. "Work Results of Liquid Precipitation Measurement Based on Radar," Leningrad State Hydrological Institute, No. 130, pp 122-131.

The possible use of radar in measuring total amount and intensity of liquid precipitation is discussed. The correlation between the magnitude of the radar echo signal and the intensity of precipitation is established. Using a differential calibration method, a radar installation can measure rain intensity for any season of the year. This calibration is applicable to any kind of radar station. It is concluded that in order to record precipitation during any period of the year (for a 100-km radius) it is necessary to have radar transmitters and receivers with a sensitivity 20 times greater than the existing models. The combined use of amplitude analyzers and computers is recommended. (Author's abstract)

35. Direskeneli, H., Seliga, T. A., and Aydin, K. 1983. "Differential Reflectivity (Z_{DR}) Measurements of Rainfall Compared with Ground-Based Disdrometer Measurements," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 475-478.

This paper presents a comparison of radar estimates of rainfall parameters above a point location on the ground in central Illinois on October 28, 1982. Differential reflectivity (Z_{DR}) radar measurements were used to derive the radar estimates while an electromechanical disdrometer system was used for the ground-based measurements. The purpose of this experiment was to assess the radar's ability to estimate drop size, rainfall rate and water content from (Z_H, Z_R) measurements. $Z_{H,V}$ are the reflectivity factors at horizontal (H) and vertical (V) polarizations and

$$Z_{DR} = Z_H/Z_V$$

$$Z_{DR}(\text{dB}) = 10 \log Z_{DR} \text{ db}$$

The dual polarization, differential reflectivity radar technique was introduced by Seliga and Bringi (1976) as a possible means of improving radar's ability to quantitatively estimate rainfall rate. Early studies and a theoretical assessment by Ulbrich and Atlas (1982) support the premise that the technique offers the possibility of improved rainfall rate measurements over other methods such as Z-R relationships. It is, therefore, important to continue testing the technique in order to improve the methodology of analysis and to determine the technique's limitations and accuracy. This study addresses these needs by employing empirical

relationships, predicted from ground-based disdrometer data, in the analysis of radar observations for the purpose of estimating rainfall rates and drop sizes. (Author's summary)

36. Doneaud, A. A., Smith, P. L., Jr., Dennis, A. S., and Sengupta, S. 1980. "A Method for Estimating Rain Volumes Over Small Areas Using Radar and Synoptic Data," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL,* pp 458-460.

    The forecasting technique is a three-stage process. First, using the stability index and the humidity derived from the morning sounding data, we estimate the average rainfall coverage over the area during the day. In the second stage, we use the rain area-rain volume correlation to estimate the rain volume. Diagrams for these two stages are presented in the earlier paper (Doneaud et al. 1979). The rain volume estimate should be adjusted according to the type of rain (frontal or instability). The third stage is the surface area adjustment.

    The estimating technique is also a three-stage process. In the first, we obtain the average rainfall coverage over the area during the day by averaging, over 12 successive hours, the maximum echo area during any one radar scan in each hour. This could also be done, less satisfactorily, using hourly rain gage reports. The second and third stages are the same as above. (Author's summary)

37. Doneaud, A. A., Smith, P. L., Dennis, A. S., and Sengupta, S. 1981. "A Simple Method for Estimating Convective Rain Volume over an Area," *Water Resources Research,* Vol 17, No. 6, pp 1676-1682.

    Previous authors have reported significant correlations between the horizontal extent of convective showers or storms and the volume of rain they produce. This paper employs that idea to develop a simplified method for estimating convective rainfall by considering only the horizontal extent and duration of the precipitation. The present analysis is based on rain gage and radar data from an area in western North Dakota. A synoptic adjustment is applied to the radar rain volume estimates. A quantity called the integrated rainfall coverage can be calculated from either gage or radar data and is found to be well correlated with the rain volumes. The maximum echo area during any one scan in 1 hr seems to be the hourly radar measurement best correlated with the rain volumes. This limited study suggests that the accuracy of the simplified method approaches that of methods using radar reflectivity data and may have operational value in some special situations. (Author's abstract)

38. Doneaud, A. A., Ionescu-Niscov, S., Priegnitz, D. L., and Smith, P. L. 1984. "The Area-Time Integral as an Indicator for Convective Rain Volumes," *Journal of Climate and Applied Meteorology,* Vol 23, No. 4, pp 555-561.

    Digital radar data are used to investigate further a simple technique for estimating rainfall amounts on the basis of area coverage information. The basis of the technique is the existence of a strong correlation between a measure of the rain area

coverage and duration called the Area-Time Integral (ATI) and the rain volume. This strong correlation is again demonstrated using echo cluster data from the North Dakota Cloud Modification Project 5-cm radars.

Integration on a scan-by-scan basis proved to be superior for determining ATI values to the hour-by-hour integration used previously. A 25-dB(z) reflectivity threshold was found suitable for the ATI calculation. The correlation coefficient on log-log plots of cluster rain volume versus ATI is approximately 0.98, indicating a power-law relationship between the variables. The exponent of that relationship is just a little higher than one, which indicates that the cluster average rainfall rate is almost independent of the storm size and duration.

A test of the relationship derived from one set of data (1980) against an independent set (1981) showed it to be consistent. Using the 1980 relationship to estimate the 1981 cluster rain volume for a given ATI, the uncertainty of the rain volume estimates was found to to be -31% to +46%. (Author's abstract)

39. Doviak, R. J. 1983. "A Survey of Radar Rain Measurement Techniques," *Journal of Climate and Applied Meteorology*, Vol 24, No. 5, pp 832-849.

    Several methods used to estimate rainfall rate R are surveyed. The distribution N(D) of drop sizes is of central importance in determining the reflectivity factor Z, attenuation rate K, and R. With single-parameter measurement techniques either of the remotely sensed parameters Z or K can be used to estimate R when gross assumptions on N(D) can be made. If N(D) can be described by a two-parameter distribution, dual measurement techniques can better estimate R without invoking these coarse assumptions. A review is made of three techniques whereby two variables might be measured: 1) dual wavelength in which Z and K are remotely measured, 2) dual polarization in which reflectivity is measured with two orthogonal polarizations, and 3) raingage-radar combinations whereby in situ point measurements of R and radar measurement of Z or R are combined to obtain a better assessment of rain over areas between gages. (Author's abstract.)

40. Doviak, R. J., and Zrnic, D. S. 1984. *Doppler Radar and Weather Observations*, Academic Press, Orlando, FL, p 458.

    This book is an excellent source for understanding radar meteorology. Chapter topics include detailed analyses of electromagnetic waves and propagation, principles of radar, Doppler spectrum of weather echoes, and meteorological radar signal processing. Additional chapters cover rain measurements, including rain gage-radar relations, observations of wind, storms, measurement of turbulence, and echoes from the precipitation-free turbulent troposphere.

41. Drufuca, G., and Zawadzki, I. I. 1975. "Statistics of Rain Gage Data," *Journal of Applied Meteorology*, Vol 14, No. 8, pp 1419-1429.

    Ten years of rain gage data are processed in order to evaluate duration, average, and maximum rate, mean square, variance, autocorrelation function and total amount for each rain storm. A spatial interpretation of these quantities is also given. Further, various rainfall rate probabilities are evaluated. (Author's abstract)

42. Eccles, P. J. 1978. "Automatic Flash Flood Warnings from Dual-Wavelength Radar-Are They Worth It?" *Preprints: Conference on Flash Floods: Hydrometeorological Aspects, American Meteorological Society, 2-3 May 1978, Los Angeles, CA*, pp 52-57.

This paper describes a prototype for a new technology, an operational instrument which has been in use in the National Hail Research Experiment for three years and has yielded much more accurate precipitation estimates, particularly of hailstorms, than those obtainable from the old technology which is a single radar. This new instrument is an X- and S-band dual-wavelength radar (XSR). The observations were secured by a primitive digital data recorder (Eccles 1975) called the Multiplexed Input NHRE Averager number I (MINA I).

The first algorithm for the practical deduction of differential attenuation from dual-wavelength radar observations of any kind and distribution of precipitation particles present in storms was made by Eccles (1975). A refined version of this analysis technique applied to carefully archived dual-wavelength radar data is described. It is shown that attenuation derived from this technique and converted to water deposition rate yields radar-estimated total water over a network of ground precipitation sensors in excellent agreement with that observed by the ground network itself, and considerably superior to that derived simply from single radar observations. (author's summary)

43. Eddy, A. 1976. "Optimal Raingage Densities and Accumulation Times: A Decision-Making Procedure," *Journal of Applied Meteorology*, Vol 15, No. 9, pp 962-971.

The requirement addressed by this study is that of estimating the rainfall over a given area within a given accuracy. Decision criteria are given explicitly, historical data sets are used to obtain the necessary statistics, optimal interpolation objective analysis (x,y,t) is used to estimate the rainfall, and specific gage density and accumulation times are deduced. Some of the hazards associated with the modeling are discussed. (Author's abstract)

44. Eddy, A. 1979. "Objective Analysis of Convective Scale Rainfall Using Gages and Radar," *Journal of Hydrology*, Vol 44, pp 125-134.

A functional representation of the morphology and evolution of a mesoscale convective storm is illustrated using HIPLEX radar reflectivities and gage rainfall data observed in Montana. The use of the function in obtaining maximum likelihood estimates of storm-total rainfall and in the optimal deployment of the sensor network is also discussed. It is shown that after four gages per individual storm-total area have been deployed, the marginal benefit realized by adding one more gage is very small if the radar reflectivity data are combined optimally with observations from these gages to produce storm-total rainfall. (Author's abstract)

45. Elvander, R. C. 1976. "An Evaluation of the Relative Performance of Three Weather Radar Echo Forecasting Techniques," *Preprints: Seventeenth Conference on Radar Meteorology, American Meteorological Society, 26-29 October 1976, Seattle, WA*, pp 526-532.

Tests of the ability of three models to make forecasts of both zero tilt reflectivities and VIL have been made. With zero tilt reflectivities, both 10- and 30-min time sequences of input data were used; only 10-min sequences of input VIL data were used. Forecasts ranging to 60 min were made with both zero tilt reflectivities and VIL data.

Results indicate that a simple cross-correlation model is the best to use when forecasts of zero tilt data are used. In fact, little loss in forecasting more intense parts of echoes resulted when forecasts were made using all the data. Therefore, we believe that the Canadian model (Austin and Bellon 1974), or a similar model using the entire PPI pattern, is the best to use when zero tilt reflectivities are being considered.

On the other hand, we have found that a linear least squares interpolation of echo centroids is the best to use with VIL data, especially when higher integer thresholds are considered. Surprisingly small rms centroid positional errors were also obtained with the VIL data. We believe this to be the result of VIL's ability to isolate and track important convective echoes in space and time. (Author's summary)

46. Galli, G. 1984. "Generation of the Swiss Radar Composite," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland*, pp 208-213.

The composite radar picture has been successfully introduced as an operational product in the Swiss weather forecasting offices and the forecasters appreciate this type of data presentation.

Almost the whole information covered by two radar stations is assembled on a single image, containing the entire Swiss territory up to a height of 12 km.

The composite is generated in real time and transmitted afterwards with a delay of about 4 min. This delay is considered to be of minor importance, because it is compensated by advantages like filling of blind zones, further reduction of clutter, and presentation of a smoothed image.

Plans call for further processing of the radar data in near real time, taking into account the vertical echo distribution and the precipitation rates measured by rain gauges in order to increase the accuracy of the precipitation estimates. (Author's summary).

47. Gilet, M., Sauvageot, H., and Testud, J. 1984. "Weather Radars Programs in France," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland*, pp 15-20.

This paper describes the present status of weather radar in France. The instruments are operated by different laboratories, attached either to the Centre National de la Recherche Scientifique or to the Weather Service, and all the developments are made in close collaboration inside cooperative research programs.

Research radars include a set of two C-band Doppler radars and the Ronsard system, which is used mainly for studies on deep tropical convection and frontal systems. The Rabelais K-band radar has been operated for more than 10 years for microphysical studies. The radar has been recently dopplerized and includes multi-polarization capabilities. Recently, dual polarization has also been added to an S-band radar operated in Clermont Ferrand. Developments are under way on UHF/VHF wind profiling.

The operational weather radar network includes 11 S- and C-band radars, of which 8 are already installed. Composite pictures are transmitted to a large number of weather stations and other users. Many improvements are planned for the following years, including the development of a new operational radar.

The research and operational radars have been used in the joint 1984 FRONTS experiment. Another experiment on frontal systems is planned for 1986 or 1987, in cooperation with other European countries. The three main objectives are a better understanding of interactions between cloud dynamics and microphysics, research on the parameterization of the convective process and development of nowcasting methods. (Author's summary)

48. Harrold, T. W., and Nicholass, C. A. 1972. "The Accuracy of Some Recent Radar Estimates of Surface Precipitation," *The Meteorology Magazine*, Vol 101, No. 1200, pp 193-205.

Results of some recent quantitative radar measurements of precipitation, made in many geographical locations, are reviewed. Reasons for variations in the measurements are discussed and methods for improving accuracy of future measurements are considered. (Author's summary)

49. Harrold, T. W., English, E. J., and Nicholass, C. A. 1973. "The Dee Weather Radar Project: The Measurement of Area Precipitation Using Radar," *Weather*, Vol 28, No. 8, pp 332-338.

The paper describes the development of the Dee Weather Radar Project. The main aim of the study was to determine the accuracy of the radar measurements of sub-catchment precipitation over periods of an hour or longer. The ultimate aim of the project was to develop a radar system to measure areal precipitation in real time on a space and time scale appropriate to the hydrological requirements for water management and river regulation. The radar used in the study was a 10-cm radar with a 2° beam width. Consideration of screening by hilly terrain, range dependence, and calibration with rain gages are all discussed. Results indicated it would take several hundred telemetering gages to provide the data in real time that could be supplied by the radar.

50. Harrold, T. W., English, E. J., and Nicholass, C. A. 1974. "The Accuracy of Radar-Derived Rainfall Measurements in Hilly Terrain," *Quarterly Journal of the Royal Meteorological Society*, Vol 100, pp 331-350.

A weather radar has been used to measure rainfall over hilly terrain in north Wales. The radar was a standard Plessey type 43S, which has a wavelength of 10 cm and a beam width to half power points of 2^{o}. Measurements were compared with those based on a raingauge network consisting of 62 tipping bucket gauges distributed over 1,000 km^2. This density of gauges was inadequate to define the hourly areal rainfall sufficiently accurately on some occasions and in these circumstances the radar-derived pattern was used to interpolate between the gauges so as to obtain an "optimum" estimate of the actual sub-catchment rainfall which was then used to evaluate the accuracy of the radar measurement.

Errors in the radar estimates were excessive unless the radar was calibrated hourly using raingauge measurements from one site. The accuracy was further increased when the horizontal drift of the rain in the wind between the radar beam and the calibration site was allowed for. These procedures will allow a mean percentage difference (regardless of sign, Y pt) between the radar and optimum estimates of 3-hr rainfall over subcatchments (typically 50 km^2) that varies from about 15 percent near the calibration site to about 20 percent at a distance of 20 km. Differences decreased as the period of integration was increased; Y was 13% for 6-hr periods compared with 20% for 2-hr periods. Y also varied with the area of comparison. For point measurements, hourly estimates differed by 37% but over an area of 500 km^2 around the calibration site, they differed by about 13%.

The main causes of error in the radar measurements seem to be (a) variations in the drop size distribution relation, (b) the spatial variation in the growth (or evaporation) which occurred between the beam and the ground, and (c) the horizontal drift of the rain caused by the wind. Probably all of these factors but in particular (b) are more important in the hilly terrain of this study than would be the case in flatter terrain. A further factor contributing to the differences between the radar and optimum estimates was the (unavoidable) error in each optimum estimate of the actual rainfall.

The accuracy of the radar estimates decreased markedly if the beam intersected the melting layer. The increased errors were reduced by introducing an empirical correction factor which is a function of the range of the sub-catchment from the radar and the height of the melting layer, but the spatial and temporal variations of the melting layer were such that it was not possible to obtain the same accuracy as when the beam was entirely within rain. (Author's summary)

51. Harrold, T. W., Nicholass, C. A., and Collier, C. G. 1975. "The Measurement of Heavy Rainfall over Small Catchments Using Radar," *Hydrological Sciences Bulletin*, Vol 20, No. 1, pp 69-76.

It is shown that radar-derived estimates of heavy localized rainfall over sub-catchments of 20 to 100 km^2 in hilly terrain in North Wales differ from optimum estimates, based on data from a network of rain gauges, by an average 13 percent if a calibration gauge is located within the sub-catchment of interest, or by 38 percent if there is no calibration gauge—the average calibration from an 18-month period being used instead. In order to make accurate measurements over very small areas (a few square kilometers), the radar should be within about 35 km of the area of interest so that errors in the estimates of surface rainfall resulting from the horizontal movement of the rain as it falls from the radar beam to the ground are minimized. The radar system used in this study is now being modified so that the data can be processed on site and transmitted in near real time to a nearby river control centre. (Author's abstract)

52. Harrold, T. W., and Kitchingman, P. G. 1975. "Measurement of Surface Rainfall When the Beam Intersects the Melting Layer," *Preprints: 16th Radar Meteorology Conference, American Meteorological Society, 22-24 April 1975, Houston, TX*, pp 473-478.

In the middle and northern latitudes, the accuracy of radar-derived estimates of surface rainfall is sometimes diminished because of the presence of the melting layer (bright band) within the radar beam. Harrold, English, and Nicholass (1974) showed that errors could be reduced significantly by applying a statistically derived correction factor which was a function of the height of the melting layer, and the range of the area of interest. However, a disadvantage of their method is that it is not clear to what extent the corrections can be applied in areas other than the hilly terrain in which they were derived. In this paper an objective method of reducing the magnitude of the errors is described and assessed. This method has the advantage over the earlier method that it can be applied in any locality.

The procedure utilizes data gathered during azimuth rotations at two angles of elevation. Ratios of the echo at the two elevations are the input to the correction procedure. These data must be averaged over time and space in order to minimize the influence on the ratio of factors other than the bright band. In the data presented here this averaging has been performed over areas 10 deg in azimuth by 1.5 km in range.

The results to date are encouraging. Once the procedure has been incorporated into the real time system, experience should be gained quickly which may lead to modifications of the procedure in order to improve the procedure further. (Author's summary)

53. Hewitt, F. J. 1971. "The Measurement of Rainfall by Radar and Satellites," *South African Journal of Science*, Vol 67, No. 3, pp 183-190.

This paper is a very general review of the development of radar-rainfall measurements and a broad overview of the use of satellites in estimating rainfall. The author concludes that ground-based radar makes possible the measurement of rainfall rates and total rainfall over large areas of country with an accuracy and convenience that cannot be easily achieved by more conventional means. Radar is particularly appropriate when rainfall rates are high and the rainfall highly localized. (author's summary)

54. Heymsfield, G. M., Ghosh, K. K., and Chen, L. C. 1983. "An Interactive System for Compositing Digital Radar and Satellite Data," *Journal of Climate and Applied Meteorology*, Vol 22, No. 5, pp 705-713.

This paper describes an approach for compositing digital radar data and GOES satellite data for meteorological analysis. The processing is performed on a user-oriented image processing system and is designed to be used in the research mode. It has a capability to construct PPIs and three-dimensional CAPPIs using conventional as well as Doppler data, and to composite other types of data. In the remapping of radar data to satellite coordinates, two steps are necessary. First, PPI or CAPPI images are remapped onto a latitude-longitude projection. Then, the radar data are projected into satellite coordinates. The exact spherical trigonometric equations, and the approximations derived for simplifying the computations are given. The use of these approximations appears justified for most meteorological applications. The largest errors in the remapping procedure result from the satellite viewing angle parallax, which varies according to the cloud top height. The horizontal positional error due to this is of the order of the error in the assumed cloud height in mid-latitudes. Examples of PPI and CAPPI data composited with satellite data are given for Hurricane Frederic on 13 September 1979 and for a squall line on 2 May 1979 in Oklahoma. (Author's abstract)

55. Hildebrand, P. H. 1978. "Iterative Correction for Attenuation of 5-cm Radar in Rain," *Journal of Applied Meteorology*, Vol 17, No. 4, pp 508-514.

The attenuation of 5-cm radar in rain is investigated theoretically for stratiform and thunderstorm drop size distributions. An iterative attenuation estimation scheme is presented. The effects of attenuation on radar precipitation measurements, and the capabilities of the attenuation estimation technique are considered for a variety of hypothetical storm sizes and errors in radar calibration, assumed temperature, and assumed drop size distribution.

This study indicates that 5-cm radar is an adequate precipitation-measuring radar for storms under about 50 dBZ, and that if calibrated correctly and used with the iterative correction scheme, the 5-cm radar can function moderately well up to about 60 dBZ. Radar calibration is seen to be a limiting criterion for attenuation

correction. The results of this study point out the need for rain gages in most situations requiring accurate rainfall measurement. (Author's abstract)

56. Hildebrand, P. H., Towery, N., and Snell, M. R. 1979. "Measurement of Convective Mean Rainfall over Small Areas Using High-Density Raingage and Radar," *Journal of Applied Meteorology*, Vol 18, No. 10, pp 1316-1326.

Techniques of measuring area-mean convective rainfall over small areas (<2,000 km^2) are investigated using data from several gage-radar rainfall measurement studies. These data suggest that for low gage densities (gage per 250-300 km^2) and for some climates (e.g., Illinois) gage-radar area-mean convective rainfall measurements may be more accurate than gage-only measurements. The same result was not supported by data from another climate, suggesting that changes in rain cell size and rain evaporation rate may affect the results. Further studies are needed to verify these suggestions. The data indicate that radar adds little to gage measurement of mean areal convective rainfall for gage densities of more than one gage per 100-200 km^2. (Author's abstract)

57. Hill, F. F., Whyte, K. W., and Browning, K. A. 1977. "The Contribution of a Weather Radar Network to Forecasting Frontal Precipitation: A Case Study," *The Meteorological Magazine*, Vol 106, No. 1256, pp 69-89.

The recent development at Malvern of techniques for the processing and transmission of composite radar data from several sites to remote centres brings nearer the possibility of providing meteorological offices with a real-time, semi- quantitative display of precipitation distribution. A case study of frontal precipitation is presented illustrating the value such a system has for mesoscale and synoptic-scale forecasting. The case is analysed using both a subjective and an objective approach. The indications are that improvements in the forecasts can be achieved for periods of 3 to 6 hr ahead. (Author's abstract)

58. Hill, F. F., Browning, A., and Bader, M. J. 1981. "Radar and Raingauge Observations of Orographic Rain Over South Wales," *Quarterly Journal of the Royal Meteorological Society*, Vol 107, pp 643-670.

Eight detailed case studies are summarized to clarify the structure and mechanism of orographically enhanced frontal rain over hills of modest height. The observations were obtained as part of a field project in south Wales in which data from a three-dimensionally scanning radar were combined with autographic raingauge data. The results show that the generation of orographic rain is consistent with Bergeron's seeder-feeder mechanism, according to which raindrops from upper-level (seeder) clouds wash out small droplets within low-level (feeder) clouds formed over the hills. It is demonstrated that the orographic enhancement is strongly influenced by the low-level wind speed. The largest enhancement of rainfall occurred in association with strong winds, and also high relative humidity, below 2 km. The radar showed that over 80% of the enhancement occurred in the lowest 1.5 km above the hills. It also showed that the periods of

enhanced rainfall were associated with the passage of pre-existing areas of precipitation. The precise value of the upwind rainfall rate was rather unimportant in influencing the orographic increment provided the rainfall rate upwind exceeded about 0.5 mm hr^{-1}. These findings are compared with the results of theoretical calculations based upon the washout model of Bader and Roach. (Author's summary)

59. Hogg, W. D. 1978. "Quality Control and Analysis of an Archive of Digital Radar Data," *Preprints: Eighteenth Conference on Radar Meteorology, American Meteorological Society, 28-31 March 1978, Atlanta, GA*, pp 150-154.

The Atmospheric Environment Service is developing a national network of C-band quantitative weather radars with a digital recording and transmission capability. Digital data from this network are used to create a national archive of good quality, easily accessible, quantitative radar data. Single-time software development permits the initiation of a radar climatology program for the entire network, and special analysis programs developed for one area of the country are readily usable at the other sites in the network. (Author's summary)

60. Holtz, C. D. 1983. "Radar Precipitation Climatology Program," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 390-393.

This paper describes and gives the results from the prototype Radar Precipitation Climatology Project designed to obtain statistics on precipitation falling within a radar region. To quantify these characteristics, distributions of rainfall in the horizontal, with intensity, with depth and duration, as well as parameters giving averages and totals for the region, have been computed and are presented here. (Author's summary)

61. Houze, R. A., Jr., Geotis, S. G., Marks, F. D., Jr., Churchill, D. D., and Herzegh, P. H. 1981. "Comparison of Airborne and Land-Based Radar Measurements During Winter MONEX," *Journal of Applied Meteorology*, Vol 20, No. 7, pp 772-783.

The first quantitative test of the lower fuselage radar on the NOAA WP-3D aircraft was obtained during the Winter Monsoon Experiment (Winter MONEX). Reflectivities measured with this radar were compared with land-based measurements obtained with the MIT WR 73 weather radar, which was located on the north coast of Borneo for the experiment. Although the interpretation of the measurements with the WP-3D radar was difficult because of its wide vertical beam and the motion of the aircraft, the coverage of the MIT radar was fully three-dimensional and the volumes sampled by the WP-3D radar beam could thereby be placed into spatial context. The measurements with the two radar systems agreed to within 1-2 dB, excellent agreement for any two quantitative radars. Radar reflectivities computed from particle images obtained aboard the aircraft differed by only 2-3 dB from the aircraft radar measurements, again quite satisfactory agreement. (Author's abstract)

62. Johnson, E. R., and Bras, R. L. 1979. "Real-Time Estimation of Velocity and Covariance Structure of Rainfall Events Using Telemetered Raingage Data-A Comparison of Methods," *Journal of Hydrology*, Vol 44, pp 97-123.

Short-term rainfall prediction in time and space requires parameter estimation in real time. This paper discusses several methods of using telemetric raingage data to estimate the non- stationary mean and variance of a rainfall event. Similarly, real-time estimation of residual covariance structure and storm velocity is discussed. The performance of the suggested techniques is illustrated with examples. The parameter estimation corresponds to a forecasting model developed by Johnson and Bras. The goal of this article is to inform other researchers of the advantages and disadvantages of different methodologies for real-time estimation of rainfall statistical characteristics. (Author's abstract)

63. Joss, J. 1981. "Digital Radar Information in the Swiss Meteorological Institute," *Preprints: Twentieth Conference on Radar Meteorology, American Meteorological Society, 30 Nov-3 Dec 1981, Boston, MA*, pp 194-199.

This paper reviews the status of radar meteorology in Switzerland. The difficulties of working in such a mountainous area with only two radars are pointed out in the paper. Complete volume scans can be completed in 10 min. The author states errors are due to influence of orography and clutter, spatial and temporal distribution of precipitation, anomalous propagation and attenuation, and the Z-R relation. The advantage of the radar mainly lies in the high spatial resolution and to a lesser degree in the absolute accuracy of measuring rain amounts. It is unlikely that radar will ever replace the rain gage, which is essential for continuous calibration and checking. (Author's abstract)

64. Kessler, E., and Wilson, J. W. 1971. "Radar in an Automated National Weather System," *Bulletin of the American Meteorological Society*, Vol 52, No. 11, pp 1062-1069.

Appropriate uses of radar in a national weather system within the next 10 to 15 years are considered. A radar network sensing precipitation reflectivity and utilizing many automatic techniques for acquiring and processing data, preparing forecasts, and communicating precipitation characteristics represents a worthwhile goal practically achievable by 1980. A suitable system would combine the information provided by radar and other sensors, would provide users with the specialized information they require at a reasonable cost, and would promote effective interpersonal and man-machine relationships. It would also readily admit new instruments and techniques as their worth is demonstrated.

The meteorological applications of reflectivity data are listed and radar data flow rates corresponding to low, moderate, and high load configurations in the envisioned

system are presented. Increasing the flow rates corresponds to increasing proportions of automatic as opposed to manual operations in the system.

The system outlined represents a preliminary goal which should be modified as new knowledge is acquired from field tests within the operational radar system and from other research. (Author's abstract)

65. Kinser, G. D., and Gunn, R. 1951. "The Evaporation, Temperature, and Thermal Relaxation Time of Freely Falling Waterdrops," *Journal of Meteorology*, Vol 8, No. 1, pp 71-82.

A theoretical and experimental study of the physical behavior of freely falling waterdrops is carried out. The influence of ventilation and environment upon the evaporation and equilibrium temperature is formulated in quantitative terms.

The theoretical approach emphasizes the vapor and heat transferred to packets of environmental air that make transient contact with the liquid sphere. The basic psychrometric equation is derived for a freely falling spherical drop. Measurements of the evaporation, equilibrium temperature, and time to reach equilibrium were carried out for single drops and compared with theory. Evaporation data are presented for drops from the largest size down to those of cloud size.

New methods and apparatus especially devised to study freely falling drops are described. (Author's abstract)

66. Klazura, G. E. 1981. "Differences Between Some Radar-Rainfall Estimation Procedures in a High Rain Rate Gradient Storm," *Journal of Applied Meteorology*, Vol 20, No. 11, pp 1376-1380.

Radar and gage data from a convective storm were analyzed with the objective of examining how much gage-estimated and radar-estimated rainfall differ in a high rainfall-rate gradient situation considering 1) the location and size of the radar contributing area, 2) whether radar-estimated rainfall was computed using maximum, average, or integrated values, and 3) the radar reflectivity factor threshold. Differences exceeding factors of 6 and 3 have been observed for individual gages and for the mean of 17 gages, respectively. (Author's abstract)

67. Koistinen, J., and Puhakka, T. 1981. "An Improved Spatial Gauge-Radar Adjustment Technique," *Preprints: Twentieth Conference on Radar Meteorology, American Meteorological Society, 30 Nov-3 Dec 1981, Boston, MA*, pp 179-186.

According to this study the applicability of individual G/R-values may vary considerably from case to case. In short-interval rainfall measurements G/R values seem to be generally applicable only to ranges of, at most, a few kilometers. Because of the great variability in the representativeness of the G/R values, in an optimal radar adjustment method, the influence of spatial variation of G/R values and the average G/R should be determined individually for each case. The method presented here combines the uniform range-dependent adjustment (by which the bias will be removed from the radar estimates) and the spatially varying adjustment method (by which radar measurement can be adjusted to fit individual gauge observations). As a result, in cases in which individual gauge values appear to be applicable, the spatial adjustment will automatically receive priority whereas in cases in which radar and gauge samples seem not to agree individually, only the bias will be removed. The weighting of these two adjustment methods is continuous between these extremes and is determined using the actual autocorrelation function of G/R for each case in combination with the local observation density.

Preliminary tests carried out using data from three different rainfall periods imply that the main adjustment method will be the range-dependent uniform adjustment or average adjustment as a special case. The spatially varying adjustment should dominate only if gauge-radar sampling errors are known to be insignificant. In real operational applications this will become even more pronounced, as the adjustment gauge networks are normally more sparse than the network used in this study. (Author's summary)

68. Koistinen, J., and Puhakka, T. 1984. "Can We Calibrate Radar By Raingages," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada,* pp 263-267.

The gauge-radar comparison, which at best is performed using log(G/R) values, may reflect several errors in radar rainfall measurements. However, in typical measurement situations it is difficult to split an observed gauge-radar ratio into parts having different physical causes. So if we search for a correlation between a precipitation parameter and gauge-radar comparisons (e.g., parameter a in disdrometer-measured Z_e-R relationship and F), the lack of such correlation does not prove that such a relationship does not exist. On the other hand, one has to be critical when interpreting gauge-radar ratios as the result of one physical reason, e.g., calibration error. This follows from the large simultaneous errors caused by things such as the variation of the Z_e-R relationship, beam overshooting, rainfall reflectivity gradients and attenuation, all of which exceed the effect of the calibration error. Consequently, rain gauges cannot replace an accurate conventional electrical calibration, which is desirable when meteorological reasons for G/R ratios are being sought after. (Author's summary)

69. Krajewski, W. F., and Georgakakos, K. P. 1985. "Synthesis of Radar Rainfall Data," *Water Resources Research,* Vol 21, No. 5, pp 764-768.

A method of generating synthetic radar-rainfall data is described. The data are generated by imposing random noise on a given, high-quality radar-rainfall field. Certain conditions are imposed on the resultant rainfall field so that the noise parameters are prespecified. The conditions pertain to the second-order statistics of the generated rainfall fields: the mean, the variance, the correlation, and the variance of the logarithmic ratio of the resultant field to the original field. Accuracy of the generation method is evaluated from implementing a test case using

Global Atmospheric Research Program Atlantic Tropical Experiment radar data. The method can be used in a number of different, mainly hydrologic, applications. These include validation of merging procedures for radar and rain gage data, testing of various methods for computing of mean areal precipitation, and sensitivity analysis of rainfall-runoff models. (Author's abstract)

70. Lambert, A. O., and Lowing, M. J. 1980. "Flow Forecasting and Control on the River Dee," *Hydrological Forecasting Proceedings of the Oxford Symposium, April 1980, Oxford, UK*, pp 525-534.

Telemetered hydrometric data from the Dee basin in north Wales have been used since December 1975 to operate real time flow forecasting models for multipurpose water resources and flood control usage. For a brief period in 1976, radar estimates of aerial rainfall were available in real time and were used by the model. The Dee telemetry/forecasting/control system is no longer experimental having now been accepted as a sophisticated tool for normal operational management. This paper seeks to explain the reasoning behind major interrelated decisions, such as choice and calibration of hydrological models, the value of radar, and the relative importance of rainfall and river gauging stations. In emphasizing the effect on these decisions on a drainage basin's natural constraints and particular conditions, some indication is given of how the adopted solutions have varied in different circumstances. The paper also considers, in more detail, some of those aspects of the hydrological model which are peculiar to the requirements of, and application to, real-time forecasting. (Author's abstract)

71. Larson, L. W. 1971. *Precipitation and Its Measurement, a State of the Art*, Water Resources Series 24, Water Resources Research Institute, University of Wyoming, Laramie, WY, p 74.

This document provides comprehensive review of the literature since 1966 for studies and articles dealing with precipitation and its measurement. Topics discussed include gages, gage comparison, gage shields, errors in measurements, precipitation data, data analysis, networks, and electronic measurements for rain and snow. A partially annotated bibliography of 350 references is included. (Author's abstract)

72. Lewis, F., Moore, P. L., and Lowry, D. A. 1978. "Use of Manually Digitized Radar Data in Forecasting Precipitation and Flash Floods," *Preprints: Eighteenth Conference on Radar Meteorology, American Meteorological Society, 28-31 March 1978, Atlanta, GA*, pp 453-456.

The National Weather Service's (NWS) system for Automation of Field Operations and Services (AFOS) will speed up the receipt and handling of weather data at forecast offices. It will also permit automatic processing of data that is not feasible at present. We have conducted several sets of experiments to test proposed uses of Manually Digitized Radar (MDR) data in the AFOS minicomputers at forecast offices. The first application would use the latest MDR data to update Probability-of-Precipitation (PoP) forecasts; the second would alert forecasters to threats of flash floods. (Author's summary)

73. Linsley, R. K., and Kohler, M. A. 1951. "Variations in Storm Rainfall over Small Areas," *Transactions of the American Geophysical Union*, Vol 32, pp 245-250.

Variation in rainfall over small areas has been a subject of considerable interest to hydrologists and meteorologists, but, because of inadequate data, little analytical work has been possible. The precipitation-gage network established for the Army-Navy NASA-Weather Bureau Thunderstorm Project and the Weather Bureau Cloud Physics Project near Wilmington, OH, included 55 rain gages at approximately 2-mile intervals. Utilizing data from this network, the authors analyzed the variations in average precipitation for storms computed from networks of differing densities and the relation between point and areal-average values of rainfall in storms. (Author's abstract)

74. Marshall, J. S., and Palmer, W. M. 1948. "The Distribution of Raindrops with Size," *Journal of Meteorology*, Vol 5, No. 1, pp 165-166.

Measurements of raindrop records on dyed filter papers were made for correlation with radar echoes. These measurements have been analyzed to give the distribution of drops with size. Except at small diameters, experimental observations can be fitted by the general relation:

$$N_D = N_O e^{-\Delta D}$$

where D is the diameter, $N_D \delta D$ is the number of drops of diameter between D and $D+\delta D$ in a unit volume of space, and N is the value of N_D for $D = 0$.

75. Martner, B. E. 1977. "A Field Experiment on the Calibration of Radars with Raindrop Disdrometers," *Journal of Applied Meteorology*, Vol 16, No. 4, pp 451-454.

Radar reflectivity factors determined from disdrometer measurements of drop spectra are compared with simultaneous WSR-57 radar measurements in two Oklahoma thunderstorms. The possibility of using a disdrometer for an in-field calibration check of a radar is examined and found to have limited usefulness for convective precipitation sampled at long ranges. (Author's abstract)

76. May, H. T. 1978. "An Examination of Manually Digitized Radar Data over a Portion of the Southeastern United States," *Preprints: Eighteenth Conference on Radar Meteorology, 28-31 March 1978, Atlanta, GA*, pp 171-176.

An examination of Manually Digitized Radar (MDR) data was undertaken to identify some of the major factors which produce the wide range of observed precipitation amounts associated with a given number. Numerous researchers have discussed the many factors affecting radar reflectivity and the Z-R relationship; some of these factors are examined for this data sample. The most notable opera-

tional use of MDR data is as an indicator of the probability of flash flooding. The probability of occurrence of a given precipitation amount corresponding to a given MDR total for a 2-, 3-, or 4-hr summation period is available from a nomogram. Four-hour totals of MDR data are available via teletype for use with transparent map overlays. The 4-hr summation period is probably used more often than any other summation period as an indication of the probability of flash flooding; therefore, a frequency distribution of 4-hr MDR totals was compiled. A limited gage-to-radar comparison of precipitation amounts was made to examine the effect of mountainous terrain on radar precipitation rate estimates. (Author's summary)

77. Meneghini, R. 1978. "Rain Rate Estimates for an Attenuating Radar," *Radio Science*, Vol 13, No. 3, pp 459-470.

A number of estimates are available for the extraction of rain rate from the measurements of an attenuating frequency radar. The estimates, which arise from various approximations for the attenuation, include at one extreme the estimate in which no correction for attenuation is made. An infinite number of higher order estimates exist which are shown in the limit to approach the Hitschfeld-Bordan solution. An error analysis is carried out for four of the estimates, taking into account the various "system" errors which include the randomness of the radar return power and the k-Z, Z-R relations as well as the offsets in the radar calibration constant. The results indicate that as these errors are more narrowly bracketed, progressively higher-order estimates can be beneficially employed. However, since the behavior of the estimates is strongly dependent on the system errors, the choice of the best estimate may be difficult without an accurate specification of these errors. Furthermore, in order for any of the estimates to provide a reliable means of rain-rate prediction in the presence of realistic errors, the attenuation must be kept small. This is usually insured for antenna pointing angles away from the horizontal at radar frequencies at the lower end of the X-band. (Author's abstract)

78. Moores, W., and Harrold, T. W. 1975. "Estimating the Distribution of Ground Clutter at Possible Radar Sites in Hilly Terrain," *Preprints: Sixteenth Conference on Radar Meteorology, American Meteorological Society, 22-24 April 1975, Houston, TX*, pp 370-373.

A computer-based method of estimating, from a digitized contour map, the distribution of ground clutter has been described and assessed. The technique also enables estimates of the clutter intensity to be made. The method is sufficiently reliable for it to be used in investigating the ground clutter at other possible radar sites. (Author's summary)

79. Muench, H. S., and Lamkin, W. E. 1976. "The Use of Digital Radar in Short Range Forecasting," AFGL-TR-76-0173, Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts, p 58.

As part of a program to improve short-range forecasts of weather conditions at aircraft terminals, a digital radar system was established at Air Force Geophysics Laboratory, Bedford, MA. The system, consisting of AN/FPS-77, digital interface, microwave transmitter-receiver, video integrator and computer, was installed in late 1972. Since that time the system has been used in conjunction with a network of 26 automated weather stations to make experimental forecasts of visibility and severe-weather conditions. The radar output of digital maps of radar intensity was found to be very convenient, but the inability of the radar to detect small water droplets limits the use in low visibility forecasting primarily to heavy rainstorms and snowstorms. In severe storms, modest success was attained in forecasting gusts, using digital maps. The large amounts of weather information from the network and radar frequently saturated the forecaster making forecasts at 15-min intervals, and relief was sought in the form of objective aids.

Preliminary relationships between radar intensity, extinction coefficient (visibility), and rainfall rate have been formulated. In addition, a technique was developed using digital radar maps to obtain motion vectors and make probability forecasts of severe weather conditions. The calibration procedure relies on intensity of ground targets (hills and towers) for day-to-day relative calibration, and absolute calibration has been limited to Z-R relations. (Author's abstract).

80. Ninomiya, K., and Akiyama, T. 1978. "Objective Analysis of Heavy Rainfalls Based on Radar and Gauge Measurements," *Journal of the Meteorological Society of Japan*, Vol 56, No. 3, pp 206-210.

An objective analysis scheme of precipitation based on raingauge and radar observations is presented. The scheme is applied to the heavy rainfalls on 21 June 1972 over the southwestern part of the Japan Islands. Obtained series of precipitation maps will reveal the behavior of the precipitation zone and suggest that this scheme is useful for surveillance of heavy rainfalls.

Though the results seem successful, the following improvements will be useful: 1) use closer isoecho levels (e.g., 8 levels), 2) use radar observations at shorter time interval (e.g., 5 min), 3) use more fine mesh (e.g., 5 or 2.5 km). These sorts of improvements can be made essentially without changing the analysis scheme. (Author's summary)

81. Osborne, L. F. 1983. "Interactive Digital Radar Analysis Using Discrete Floating Volumes," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 575-578.

Automated processing and analysis have become mainstays for researchers working with digital radar data recorded during meteorological research activities. This type of automation has proceeded along the paths of real-time analysis and post analysis.

The post-analysis procedures are necessary to study in intricate detail those aspects relating to radar data which can only be accomplished by meticulous review of the data. This time-consuming study is performed in either a batch or interactive computer environment. While batch processing permits an objective study of vast amounts of radar data for the purpose of echo identification and morphology, it is the interactive procedures which allow individual echo case studies to be explored.

The purpose of this paper is to describe briefly a high-speed interactive analysis software package useful in the interpretation of digital radar data. (Author's summary)

82. Ostlund, S. S. 1974. "Computer Software for Rainfall Analyses and Echo Tracking of Digitized Radar Data," NOAA Technical Memorandum ERL WMPO-15, National Oceanic and Atmospheric Administration, Boulder, CO, p. 82.

    An excellent review of the software currently available for the analysis of rainfall and the tracking of storm echoes by use of the digital radar.

83. Parrish, J. R. 1981. "WSR-57 Radar Observations during the Landfall of Hurricane Frederic," *Preprints: Twentieth Conference on Radar Meteorology, American Meteorological Society, 30 Nov - 3 Dec 1981, Boston, MA*, pp 99-103.

    Twenty-six hours of good quality digital radar data were collected from the WSR-57 radar at Slidell, LA, during the landfall of Hurricane Frederic. A portion of this data corresponding to the storm's nearest approach to Slidell has been processed and analyzed.

    Comparison of radar-derived rainfall estimates with amounts by rain gages within 230 km of the radar during this period are consistent with other studies of tropical systems, such as radar/gage comparisons over the southern Florida peninsula described by Woodly and Herndon (1969) and those reported in the GATE Radar Rainfall Atlas by Hudlow and Patterson (1979). Further work with radar rainfall compositing is being carried out at NHRL to evaluate land-based radar's effectiveness for estimating storm total rainfall.

    Some aspects of Frederic's convective changes upon landfall as seen by radar reflectivity have been described, especially the rapid development of a storm-stationary maximum in the hurricane's north eye wall. This area corresponds to the heaviest property damage incurred along the coast. A greater understanding of land effects on the storm circulation is needed to improve local forecasts and warnings. Future utilization of mobile digital radar recorders, in conjunction with aircraft observations, is planned to further document hurricanes during the critical landfall event. (Author's summary)

84. Parrish, J. R., Burpee, R. W., Marks, F. D., Jr., and Grebe, R. 1982. "Rainfall Patterns Observed by Digitized Radar During the Landfall of Hurricane Frederic," *Monthly Weather Review*, Vol 110, No. 12, pp 1933-1944.

In September 1979, two research teams traveled to the coastal area in the path of Hurricane Frederic to record observations of the storm's rainbands with mobile radar recorders. The researchers were in position at the National Weather Service offices at Slidell, LA, and Pensacola, FL, a few hours before Frederic's outer convective bands reached the Gulf Coast. Although the recorder taken to Pensacola was damaged in transit, the recording system at Slidell collected digital data for 26 hr as Frederic moved ashore at 6 to 7 m/s^{-1}, approximately 125 km to the east of Slidell. Calculations of storm-total rainfall indicate that local rainfall maxima tended to occur in two general areas: 1) parallel to the coast near the point of landfall, with a northward extension approximately along Frederic's track, and 2) on a long band oriented from south-southeast to north-northwest approximately 50 km to the west of the storm track. The storm-total rainfall maximum along the coast was explained by a rapid increase in the intensity and area coverage of deep convection in mesoscale rainbands in the north eye wall that occurred as the north eye wall interacted with the coastline.

Rain gage-radar comparisons indicate that the storm-total rainfall estimated by the radar is probably within a factor of 2 of the true value. Maximum rainfall totals measured by gages and determined by radar were approximately 250 mm. Frederic's maximum accumulated rainfall was slightly below average, relative to other hurricanes that have made landfall along the Gulf Coast of the United States. During the 4 hr that the most intense convection in the north eyewall was near the coast, maximum hourly rainfall rates were 50 to 75 mm. In this 4-hr period, 3 percent of the land area within 100 km of the center had hourly rainfall greater than 50 mm/hr^{-1} and 39 percent of the same area had rain rates of 25 to 50 mm/hr^{-1}. Land areas with the greatest wind damage were highly correlated with the location of radar-observed reflectivities greater than or equal to 41 dB(Z). Analyses of time series of radar reflectivities and 5-min peak wind gusts at the surface indicate that the maximum surface winds near the coast occurred a few kilometers inside the radar eye. (Author's abstract)

85. Puhakka, T. 1975. "On the Dependence of the Z-R Relation on the Temperature in Snowfall," *Preprints: 16th Radar Meteorology Conference, American Meteorological Society, 22-24 April 1975, Houston, TX*, pp 504-507.

Radar measurements of precipitation are based on the approximate relationship between the radar reflectivity factor A (measureable by radar) and the precipitation rate R

$$Z = AR^b$$

Coefficients A and b depend on the size distribution and on the falling velocities of the precipitation particles. Thus A and b are not universal constants but vary considerably from case to case. One of the main problems in the quantitative measurements of precipitation by radar is to find a method by which the best possible values for A and b could be determined in each individual case.

One possibility is the use of a reference rain gauge as suggested, for example, by Wilson (1970). This method has been proved advantageous in rainfall, but it cannot be used easily in snowfall measurements since heretofore there has been no practical, reliable instrument by which the amount of snow could be measured accurately for references to the radar. The present study investigates the possibilities of using the mean surface temperature as a predictor of the appropriate Z-R relation in snowfall.

The results indicate that the value of coefficent A in the Z-R relation $Z = AR^b$ increases with the mean surface temperature below -1° C. After a possible maximum at about -1° C, the value of A possibly decreases with increasing temperature as the temperature 0° C is approached. This study did not give much information about the variability of A at some particular temperature, but it appears obvious that between surface temperatures of 4° C and 0° C, where the value of A changes most with the mean surface temperature, the scatter in A at some particular temperature might also be largest. (Author's conclusions)

86. Puhakka, T., and Ruostennoja, K. 1984. "Some Problems Related to Cartesian Space Analysis of Digital Radar Data," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland*, pp 166-171.

Artifacts caused by interpolating coarse polar radar data into a Cartesian coordinate system are most pronounced in cases with horizontally wide vertical discontinuities, and their appearance and shape depend on the interpolation method used. Elimination of artifacts is difficult. It has even been suggested that the best way of dealing with them may be to "leave them alone."

In situations very badly disturbed by artifacts, these can indeed be identified and misinterpretations avoided, but the real structures of the echoes may be extremely difficult to deduce in such cases. On the other hand, if artifacts are not very strong, these cannot be identified properly and the danger of misinterpretation is great.

Using radar data collected before and after the instant we are analysing, artifacts can be reduced to some extent by assuming pattern movement is quasistationary and using a dynamical interpolation scheme. If the pattern is not quasistationary, if it does not move, or if its movement is erroneously estimated, results will not improve.

The method presented here is a very elementary one. Better and more complicated methods could perhaps be developed where the physics of the spatial and time evolutions of echoes are taken more completely into account. Further improvement may be obtained by more advanced interpolation schemes which should, in particular, be able to handle discontinuities typical to radar echoes. Methods may also be improved by using some pattern recognition principles in which beam pattern effects are included. (Author's summary)

87. Reynolds, D. W. 1978. "An Intensive Analysis of Digital Radar, Raingage and Digital Satellite Data for a Convective Cloud System on the High Plains of Montana," *Preprints: Eighteenth Conference on Radar Meteorology, American Meteorological Society, 28-31 March 1978, Atlanta, GA,* pp 310-317.

The Bureau of Reclamation is involved with a large field program over a particular area of the high plains of the western US. The program, called HIPLEX (High Plains Experiment) is a weather modification program attempting to increase precipitation by seeding summertime convective clouds and cloud systems. In any weather modification program, the measurement most often sought after is that of precipitation. The most direct method to obtain this is through use of rain gages. However, the target area for the HIPLEX, the Miles City, MT (MLS) site, is 17,671 km^2. The high-density raingage network northeast of MLS covers only 1,689 km^2. Therefore, much of the precipitation cannot be measured directly. In order to compensate for this, remotely sensed rainfall measurements must be made. Radar provides one method for making these measurements. A 5-cm (C-band) radar is located at the Miles City site. Thus, using appropriate Z-R relationships, one might obtain good rainfall estimates. However, there is one other remote measuring device capable of monitoring clouds and cloud systems, but as yet it is still being tested for making remote rainfall measurements. This is the SMS-GOES (Synchronous Meteorological Satellite/Geosynchronous Operational Environmental Satellite) satellite positioned 35,800 km above the equator. The satellite orbit is nearly circular, revolving at the same speed as the earth rotates, thus maintaining a stationary position over the same point on the earth's surface.

This study attempts to use the highest quality data set available, i.e., digital radar, digital satellite, and high density rain gage data, to further explore their relationships. Results will hopefully provide new insights into the ability of the satellite to provide quantitative measurements of precipitation. (Author's summary)

88. Reynolds, D. W., and Smith, E. A. 1979. "Detailed Analysis of Composited Digital Radar and Satellite Data," *Bulletin of the American Meteorological Society,* Vol 60, No. 9, pp 1024-1037.

A technique is developed to digitally composite satellite and radar imagery in a common coordinate reference frame. Results obtained from using Geosynchronous Operational Environmental Satellite (GOES) visible and infrared data, 5-cm radar data, and recording raingage data are presented. The composite displays are created on Colorado State University's All-Digital Video Imaging System for Atmospheric Research (ADVISAR), an interactive image processing system that uses modern high fidelity digital video display technology. An efficient methodology based on analytic transforms for remapping dissimilar digital image formats into common map projections is discussed. Applications of multi-sensor composite images are demonstrated with the use of two case studies. The technique is shown to enhance our understanding of (a) convective development, (b) organization of mesoscale features as they relate to the synoptic scale, (c) severe storm development, and (d) precipitation mechanisms. Our final comments concern the compositing technique's potential for on-line interactive forecast systems, particularly in terms of an embedding approach. (Author's abstract)

89. Riedl, J., Lang, P., and Attmannspacher, W. 1984. "On the Accuracy of Areal Precipitation Measurements by Aid of Radar," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland,* pp 268-269.

    Many results about the accuracy of radar-measured rain amounts are found in the literature. This study, based on few cases of areal amount of rain measured for hydrometeorological purposes, should give a first answer on the accuracy of different ways of calculating the areal precipitation from the measured radar reflectivity (dBZ). (Author's abstract)

90. Riley, M. M., and Austin, G. L. 1983. "The Information Content of 3-D Volume Scan Weather Radar Images and Its Implications for the Transmission of These Data to Remote Sites," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September, 1983, Edmonton, Alberta, Canada,* pp 375-377.

    The purpose of this study is twofold. The first and most important question under investigation is whether meteorological radar information can be transmitted in unprocessed form from a remote weather radar installation to a central processing facility using standard telephone line equipment so that a complete hemispherical radar scan can be collected on the order of every 5 min. The second question to be answered is how much computer memory would be required at the remote radar site to buffer the large amount of data to be transmitted in the case where no mass storage device exists for data buffering. (Author's abstract)

91. Rumyantsev, V. A., and Kondrat'ev, S. A. 1981. "Use of Radar Data in a Distributed-Parameter Hydrodynamic Model for Rainfall," *Meteorologiya i Girologiya,* No. 3, pp 86-92.

    A hydrodynamic model for rain runoff with distributed parameters has been tested on a rainwater flood on the River Polomet; this enables one to incorporate the topography of the catchment area, the spatial variability in the hydrophysical parameters of the soils, and the evaporation from the catchment surface. The calculations are based on information on the precipitation distribution derived from a radar method and also from the ground-level rain-gauge network. The calculations show that these distributions are inadequate, which is due to the imperfect calibration of the radar. (Author's abstract)

92. Schilling, W., and Okroy, R. 1981. "Short Term Forecasting of Spatially Distributed Rainfall in Urban Areas," *Preprints: Second International Conference on Urban Storm Drainage, Urbana, IL, 14-19 June 1981*, pp 40-48.

    The Kalman filtering approach is applied to short-term quantitative precipitation forecasts. The forecasting model is based only on historical rain gage data.

Model parameters are estimated by Matalas' stochastic multivariate simulation model. Some numerical results and their evaluation are given. (Author's abstract)

93. Schilling, W. 1984. "Real-Time Estimation and Forecasting of Spatially Distributed Areal Rainfall," *Water Science Technology*, Vol 16, pp 327-348.

After a short demonstration about the need for operational rainfall forecasts, a literature survey, constraints for model development and definition of criteria of model performance, a simple multivariate autoregressive model is presented that forecasts point rainfall spatially distributed, for short lead times, quantitatively and automatically. For model operation, only remotely transmitted standard raingage data are necessary.

The model is expanded to also forecast and estimate areal rainfall from point measurements using the Kalman filter technique and the theory of regionalized variables.

The Kalman filter model is demonstrated to be superior for areal rainfall estimation (compared to the the Thiessen procedure) as well as for areal rainfall forecasting compared to trivial forecasts and the point forecasting model mentioned above. (Author's abstract)

94. Schroeder, M. J., and Brueni, L. 1976. "Computer Processing of Digital Radar Data Gathered During HIPLEX," *Preprints: Seventeenth Conference on Radar Meteorology, American Meteorological Society, 26-29 October 1976, Seattle, WA*, pp 453-461.

HIPLEX radars are capable of generating one 2,400-ft, 800-bpi magnetic tape every hour. With this large amount of data, a concerted effort has been made to eliminate unreliable and insignificant echo data so as to decrease the data set and make only useful radar data available to the scientific community. A very real consideration was the type of computer and the amount of computer time available to the HIPLEX Program. With this in mind, a processing system was designed to integrate manual and computer techniques where they were most efficient and effective. Manual intervention is necessary in any computerized system. The final output is only as reliable as the original data and the programs manipulating it. The flow of digital radar data has a sufficient amount of human intervention to maintain quality control, but the system is automated to the extent where most, if not all, the digital radar tapes can be analyzed.

Modifications to a data processing system are inevitable. This system is no exception. Although no significant changes are expected to be made to algorithms or magnetic tape files, methods to decrease processing time are being investigated, in particular automated cell identification and tracking. (Author's summary)

95. Schroeder, M. J., and Klazura, G. E. 1978. "Computer Processing of Digital Radar Data Gathered During HIPLEX," *Journal of Applied Meteorology*, Vol 17, No. 4, pp 498-507.

Digital radar data are being collected as part of the Bureau of Reclamation's High Plains Cooperative Program (HIPLEX). The radars used in this study are sensitive, narrow-beam, 5-cm wavelength systems which record echo data on computer-compatible magnetic tape. The antenna scans continuously in a volume mode of 360^{o} in azimuth and 12^{o} in elevation. The time interval for a complete volume scan is approximately 5 min. An overview of the HIPLEX radar operational program and data flow from collection to analysis products is presented.

Computer programs to edit, correct, compress, process, and archive the data have been developed and tested. Examples and descriptions of printed, microfiche, and magnetic tape output are described. These include composite maximum reflectivity and echo top displays, an equivalent reflectivity file, and a case study summary file which contains location, area, volume, rain, and motion information for cells that were identified and tracked. It is shown that the flow of digital radar data has a sufficient amount of human intervention to maintain quality control in an evolving computer environment. (Author's abstract)

96. Seliga, T. A., and Bringi, V. N. 1976. "Potential Use of Radar Differential Reflectivity Measurements at Orthogonal Polarizations for Measuring Precipitation," *Journal of Applied Meteorology*, Vol 15, No. 1, pp 69-76.

The potential use of differential reflectivity measurements at orthogonal polarizations to determine rainfall rate is examined. The method involves measurements of Z_H and Z_V (the radar reflectivity factors) due to horizontally and vertically polarized incident waves, respectively. The differential reflectivity, $Z_{DR} = 10 \log(Z_H/Z_V)$, which should be precisely determinate, occurs as a result of the distortion of raindrops as they fall at terminal velocity. The approximate theory of Gans for electromagnetic scattering by spheroids is applied to the distorted raindrops. Assuming a general exponential form for the raindrop size distribution, equations are derived relating the distribution parameters to the measurements. The determination of rainfall rate follows directly. Finally, the sensitivity of the distribution parameters to radar inaccuracies is examined, and several methods of implementing the measurements are suggested. It is concluded that good estimates of rainfall rate using a single non-attenuating wavelength radar are possible under ideal conditions. (Author's abstract)

97. Seliga, T. A., Bringi, V. N., and Al-Khatib, H. H. 1980. "Differential Reflectivity Measurements of Rainfall Rate: Raingage Comparisons," *Preprints, Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL*, pp 440-445.

This paper reviews Seliga and Bringi's technique, presents error analysis of a single estimate of rainfall rate, and compares areal measurements of rainfall rate made by the Z_{DR} technique with raingauge measurements and conventional radar measurements. (Author's summary)

98. Seliga, T. A., Bringi, V. N., and Al-Khatib, H. H. 1981. "A Preliminary Study of Comparative Measurements of Rainfall Rate Using the Differential Reflectivity Radar Technique and a Raingage Network," *Journal of Applied Meteorology*, Vol 20, No. 11, pp 1362-1368.

Radar measurements of average rainfall rate over two separate 550 km^2 areas are compared with raingage measurements in the same areas over time intervals of ~1 h. The measurements were performed to test the differential reflectivity (Z_{DR}) technique of Seliga and Bringi (1976), which provides a means of estimating rainfall rate (R) by combining measurements of radar reflectivity factors at horizontal (Z_H) and vertical (Z_V) polarizations; Z_{DR}(dB) is defined as the ratio of these reflectivities, i.e., $Z_{DR} = 10 \log(Z_H/Z_V)$. Results from an experiment performed near Chicago, IL, on 9 August 1978, using the University of Chicago-Illinois State Water Survey (CHILL) radar and the Illinois State Water Survey's Hydrometeorological Area Project (CHAP) raingage network are presented. Z_{DR} estimates of rainfall rate compared very favorably with the raingage measurements and were significantly better than estimates obtained from two Z-R relationships, one of which was obtained by raingage calibration. Over one of the 550-km^2 areas, the Z_{DR} method measured 86 percent of the rainfall recorded on 26 raingages during an observational period of 80 min, and over the other, 117 percent of the rainfall recorded on 27 raingages was obtained during a 40-min period. (Author's abstract)

99. Seliga, T. A., Aydin, K., and Direskeneli, H. 1983. "Disdrometer Measurements During a Unique Rainfall Event in Central Illinois and Their Implications for Differential Reflectivity Radar Observations," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 467-474.

Disdrometer measurements in the rainfall event of October 6, 1982 in central Illinois provided an excellent opportunity to develop empirical relationships between the radar observables (Z_H,Z_V) and rainfall parameters. The results are presented as power law relationships between both R/Z_H and M/Z_H with Z_{DR}(dB). Z_{DR}(dB) was also found to satisfy either a linear or power law relationship with D_o, the median volume diameter. Model computations suggest that the scheme should produce excellent results for estimating R using the Z_{DR} technique. These relationships are important in that they should provide a better means of utilizing (Z_H,Z_{DR}) radar measurements for estimating rainfall parameters (R,M,D_o) than is possible assuming the form of a two-parameter drop size distribution. Finally, model computations suggest that the Z_{DR} technique is superior to Z-R relationship schemes and should produce excellent estimates of rainfall rate. (Author's summary)

100. Seliga, T. A., Aydin, K., and Direskeneli, H. 1984. "Comparison of Disdrometer-Derived Rainfall and Radar Parameters with Differential Reflectivity Radar Measurements during MAPOLE '83," *Preprints: Twenty-second Conference on Radar*

Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland, pp 358-363.

The results of this comparative study are very encouraging in that the disdrometer-derived empirical relationships for interpreting (Z_H, Z_{DR}) in terms of (R, D_0) give excellent results. The computed radar observables also yielded similar good agreement.

In addition to the comparisons, the results demonstrate the importance of drop-size sorting due to different fall velocities when comparing radar and ground-based measurements of rainfall. The procedure of accounting for this sorting in the disdrometer measurements also has relevance to the study of transient storm behavior. (Author's summary)

101. Seliga, T. A., Aydin, K., and Direskeneli, H. 1986. "Disdrometer Measurements During an Intense Rainfall Event in Central Illinois: Implications for Differential Reflectivity Radar Observations," *Journal of Climate and Applied Meteorology*, Vol 25, No. 6, pp 835-846.

Empirical relationships for estimating rainfall rate, liquid water content, and median volume diameter from radar measurements of reflectivity factor and differential reflectivity are derived from a disdrometer record of a highly variable, heavy rainfall event in central Illinois. Comparisons with relationships representing exponential and gamma model drop-size distributions are made. Simulations, employing these and Z-R relationships for rainfall estimation, are performed. Statistical measures are tabulated for comparing results. These show an excellent agreement between the disdrometer-and radar-derived rainfall parameters when the latter are obtained from the empirical relationships. (Author's abstract)

102. Sengupta, S., Smith, P. L., Jr., Dennis, A. S., and Doneaud, A. A. 1980. "Comparing the Regression Relationships Between Radar and Gage Rainfall Estimates," *Preprints: Nineteenth Conference on Radar Meteorology, 15-18 April 1980, Miami Beach, FL*, pp 461-466.

In an essential weather modification experiment, such as HIPLEX-1, an important aspect of the study is to compare rainfall estimates from radar and the rain gages for seeded and unseeded samples. Studies will also be extended to examine whether the Z-R relationships are different for the seeded and non-seeded cases.

The objective of the study here is to compare relationships between the radar-estimated rainfall (RER) and the gage-estimated rainfall (GER) for seeded and unseeded samples. We have also examined the relationships under the synoptic stratification of the subpolar and subtropical air masses.

The study showed that the distributions of RER and GER in both the seeded and unseeded samples are skewed and resemble very closely the log normal distribution. Also, the logarithmic transformation of the variables has reduced the skewness of the data and increased the values for the coefficients of determination.

The analysis of covariance is applied to compare the slopes of the regression lines under the assumption of linear additive model for the predicted value of the dependent variable. The analyses on the original and the transformed variables show that seeding does not change the slope of the regression line significantly. (Author's summary)

103. Serafin, R. J., and Carbone, R. 1984. "Status and Trends in Radar Meteorology in the United States: 1984," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland*, pp 9-14.

In this paper, we will provide an overview of the status of our field in the United States at this time. We will discuss research needs and research facilities. Operational use of meteorological radar for warning and forecasting purposes will also be considered. Another topic of considerable importance to the long-term health of our field is radar meteorological education, and it is in this area that there is cause for some concern. (Author's abstract)

104. Shore, G. 1984. "Time-Lapse Radar Imagery Applied to Short-Term Forecasting at a Broadcast Meteorological Facility," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland*, pp 214-219.

These results suggest that wider application of the real-time, time-lapse radar technique could prove an increasingly valuable tool for nowcasting and short-term forecasting, especially in severe weather. Rapid dissemination of updated weather information is of prime concern to the operational forecaster. The media meteorologist is in the uniquely difficult position of having a multitude of other tasks to perform to produce and present the weathercast as well. Under these constraints, the media meteorologist has a special need for time-saving techniques, especially when the situation becomes a threat to life and property. This method has certainly been a tremendous help to the meteorologists at KJRH-TV. More recently, in the worst flooding ever to hit Tulsa, intense thunderstorms dumped 30 cm of rain in 5 hr. The time-lapse showed the continual redevelopment of the storms in a unique way that, at least for us and our viewers, helped make the extreme nature of the event readily apparent earlier than might have been possible, perhaps saving lives in the process. (Author's summary)

105. Silverman, B. A, Roger, L. K., and Dahl, D. 1981. "On the Sampling Variance of Raingage Networks," *Journal of Applied Meteorology, American Meteorological Society*, Vol 20, No. 12, pp 1468-1478.

A study has been conducted which examines the sampling variance of raingage networks, the most commonly used precipitation estimating system. The study is based on the use of computer-simulated isohyetal patterns of known characteristics (absolute ground truth) which were calibrated against measured isohyetal patterns from convective storms that are reported in the literature. The sampling variance of raingage networks is quantitatively related to both the raingage density and the characteristics of the isohyetal pattern. It was found that the sampling variance or coefficient of variation is inversely proportional to the number of gages per surface rain cell and directly proportional to the gradient of rainfall.

These results have been used to assess the relative contribution of the sampling variance of raingage networks and the natural variability of rainfall to the estimated experimental unit sample size requirements for evaluating precipitation augmentation experiments. The convective storm rainfall data for the Miles City, Montana, area, gathered as part of the Bureau of Reclamation's HIPLEX (High Plains Cooperative Program), formed the basis of this analysis. For these rainfall characteristics, it was found that sampling variance is responsible for no more than 10% of the total sample size requirement with a gage density of at least an average of four gages per storm (gage density on the order of 80 km^2 per gage). The contribution of network sampling variance to the sample size requirement becomes significant for gage densities less than one gage per storm or for significantly lower rainfall variabilities. (Author's abstract)

106. Smith, P. L., Jr., Cani, D. E., Dennis, A. S., and Miller, J. R., Jr. 1975. "Determination of Z-R Relationships for Weather Radar Using Computer Optimization Techniques," Final Report, Contract No. 14-06-D-6660, Division of Atmospheric Water Resources Management, Bureau of Reclamation, US Department of the Interior, Denver, CO, p 73.

Quantitative radar data were collected from a 10-cm radar data set in western North Dakota during the summer of 1972 in connection with a randomized pilot project of cloud seeding. The radar data were recorded on magnetic tape for subsequent computer reduction and analysis.

The computed radar reflectivity factors have been compared with rain gage observations collected by a network of 22 recording rain gages to obtain a relationship between hourly rainfall accumulation and the observations of the radar reflectivity factor A. The relationship was obtained by applying a computer optimization technique. The resulting formula is $Z = 155R^{1.88}$. Comparison of point and area rainfall estimates obtained by applying this formula to estimates based on a network of 80 conventional rain gages in the area leads to the following conclusions:

1. The absolute radar calibration was apparently maintained to within + or -1 dB during the summer.
2. With such accurate calibration, radar can lead to estimates of areal rainfall over the season within 10% to 15% of the rain gage estimates even using a standard Z-R relationship such as the well-known Marshall-Palmer relationship.
3. Some further improvement can be obtained by using an optimized Z-R relationship appropriate to the area, such that very close agreement can be obtained in terms of total rainfall accumulation over a season.

Significant variations remain in estimates of daily areal rainfall and in point rainfall accumulations.

4. For operational measurement of areal rainfall by radar, corrections for evaporation and other meteorological variables will be necessary. Although in principle the optimization could be done on a daily basis, reducing the variance contributed by meteorological variables, it is doubtful that a sufficiently large data sample could be obtained in a single day to prevent sampling bias. (Author's abstract)

107. Staggs, D. W. 1980. "Improving Rain Gage Network Measurement Accuracy Utilizing Radar Computed Rainfall," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL*, pp 467-469.

Hydrological research using multi-year records gives solutions to rainfall problems with accuracies adequate for engineering problems of past decades. This type of data is inadequate for certain problems in today's society, which requires real-time management of water resources. Human health or life and the prevention of destruction to property often depend on accurate, real-time rainfall measurement.

The widespread use of radar to improve the accuracy of rain gage measurements has been described by Wilson (1970) Brandes (1975), and Wilson and Brandes (1979). This paper proposes a modification of the Brandes method of correction which reduces the total number of telemetered gages needed for the real-time determination of gage-radar (G-R) ratios to use with the single storm watershed management.

The real-time mating of the computer and the digital video processor to process reflectivity signatures, attenuation factors, polarization ratios or Doppler spectra offer the prospect of completely measuring the rainfall without adjustment ratios derived from remote rain gages. (Author's summary)

108. Stout, G. E., and Mueller, E. A. 1968. "Survey of Relationships Between Rainfall Rate and Radar Reflectivity in the Measurement of Precipitation," *Journal of Applied Meteorology, American Meteorological Society*, Vol 7, No. 7, pp 465-474.

Numerous investigations have been made in the last two decades including direct measurements of radar reflectivity and rainfall amount, as well as indirect measurements of the raindrop size spectra. Calculations of the reflectivity factor and rainfall rate from these spectra can be made and the relationships determined. Both methods are discussed, and a summary of the relationships is presented.

These relationships show differences in excess of 500% in rainfall rate at the same reflectivity. These large differences are primarily associated with differences in geographic locality. In addition, there are smaller differences on the order of 150% that can be attributed to different types of rain or different synoptic conditions.

Some data are available which are indicative of the differences in the relationship on a given day, depending upon the location within the storm which is sampled. This is briefly described and in only one case out of 18 is there a significant difference.

Estimates of the effects of evaporation, accretion, and coalescence on the relationship are made and show some of the reasons for the differences in the relationships noted at different geographical locations. The accuracy of the relationships is investigated with attention directed to the evaluation of total storm amounts. It is shown, in general, that the relationships introduced less uncertainty than the uncertainty in obtaining a radar measurement of the reflectivity. (Author's abstract)

109. Suomi, V. E., Fox, R., Limaye, S. S., and Smith, W. L. 1983. "McIDAS III: A Modern Interactive Data Access and Analysis System," *Journal of Climate and Applied Meteorology*, Vol 22, No. 5, pp. 766-778.

A powerful facility for meteorological analysis called the Man Computer Interactive Data Access System (McIDAS) was designed and implemented in the early 1970's at the Space Science and Engineering Center of the University of Wisconsin-Madison. Hardware and software experience gained via extensive use of that facility and its derivatives have led to a newer implementation of McIDAS on a larger computer with significant enhancements to the supporting McIDAS software. McIDAS allows remote and local access to a wide range of data from satellites and conventional observations, time lapse displays of imagery data, overlaid graphics, and current and past meteorological data. Available software allows one to perform analyses of a wide range of digital images as well as temperature and moisture sounding data obtained from satellites. McIDAS can generate multicolor composites of conventional and satellite weather data, radar and forecast data in a wide variety of two- and three-dimensional displays, as well as time-lapse movies of these analyses. These and other capabilities are described in this paper. (Author's abstract)

110. Tsonis, A. A., Bellon, A., and Austin, G. L. 1981. "The Evaluation of Predictive Schemes for the Growth or Decay of Rain Areas," *Preprints: Twentieth Conference on Radar Meteorology, American Meteorological Society, 30 Nov-3 Dec 1981, Boston, MA*, pp 174-178.

In this study extrapolation techniques were applied in order to forecast the total flux (or area) of a cell. Of those techniques tested, linear extrapolation was found to give the smallest errors. The mean and the standard deviation of the percentage errors increased with the length of the forecast period. The duration of data that was used to fit the extrapolation schemes was varied, and an interval of 30 minutes was found to be most appropriate. It was suggested that this is due to two opposing factors, one acting in establishing the trend and the other in increasing the possibility of changes in the character of the cell. Comparison of the results with those obtained by the "status quo" assumption shows that these types of extrapolation techniques really do not yield significant forecast improvements. It was felt that this could be due to either the failure of the method to follow changes in the flux when growing cells start to decay or the variability of the flux from one time step to another dominating a weakly defined trend.

Attempts to forecast rain accumulation at the ground have yielded generally similar results. However, the results from this study were obtained from long-lived cells, and it may be that they are not valid for short-lived cells.

An application of the cell flux forecasts to cloud seeding experiments was also briefly discussed. Recent results suggest that they may be a possible input in the design and evaluation of seeding experiments. (Author's summary)

111. Twomey, S. 1953. "On the Measurement of Precipitation Intensity by Radar," *Journal of Meteorology*, Vol 10, No. 1, pp 66-67.

The article summarizes rainfall studies done in Australia from November 1950 to June 1951. Distribution curves varied considerably over short time periods with no one-to-one correspondences between drop-size distributions and precipitation rates. The author concluded that radar methods can give only an approximate measure of precipitation rate; the value deduced from the radar echo may be in error by a factor of 2:1 either way, and this randomly distributed error is independent of instrumentation or procedure adopted.

112. Ulbrich, C. W., and Atlas, D. 1975. "The Use of Radar Reflectivity and Microwave Attenuation to Obtain Improved Measurements of Precipitation Parameters," *Preprints: Sixteenth Conference on Radar Meteorology, American Meteorological Society, 22-24 April 1975, Seattle, WA*, pp 496-503.

The object of this work is to show how the use of simultaneous remote measurements of two rainfall-related quantities can produce improved measurements of precipitation parameters such as rainfall rate and liquid water content. The improvement in the accuracy of measurement is demonstrated by comparing the results obtained using one of these methods to those which are found using the Joss-Waldvogel (1970) empirical relationship. (Author's summary)

113. Vogel, J. L. 1984. "Potential Urban Rainfall Prediction Measurement System," *Water Science Research*, Vol 16, pp 349-362.

Continued growth of urban regions and more stringent water quality regulations have resulted in an increased need for more real-time information about past, present, and future patterns and intensities of precipitation. Detailed, real-time information about precipitation can be obtained using radar and raingages for monitoring and prediction of precipitation amounts. The philosophy and the requirements for the development of real-time radar prediction-monitoring systems are described for climatic regions similar to the Midwest of the United States.

General data analysis and interpretation techniques associated with rainfall from convective storm systems are presented. (Author's abstract)

114. Wiggert, V., and Ostlund, S. 1975. "Computerized Rain Assessment and Tracking of South Florida Weather Radar Echoes," *Bulletin of the American Meteorological Society*, Vol 56, No. 1, pp 17-26.

Weather radar power can be electronically assessed and digitally quantified within many small "range bins." The tape-recorded output from a radar digitizer linked to the Miami WSR-57 is being processed post hoc by a sequence of computer programs written at the Experimental Meteorological Laboratory. One program assesses radar-derived rainfall rates and total rain volumes over preselected areas and for preselected time periods; another isolates and tracks radar echoes and, while so doing, calculates the rainfall from each echo as it grows, moves, splits, merges, or dies. Sample results are displayed and future applications discussed. (Author's abstract)

115. Wilk, K. E., and Kessler, E. 1970. "Quantitative Radar Measurements of Precipitation," *Meteorological Monographs*, American Meteorological Society, Vol 11, No. 33, pp 315-329.

Radar applications for the measurement of areal precipitation are reviewed. The NSSL signal processing and digital system is described in detail, as are techniques for producing processed data suitable for input in meteorologic and hydrologic analyses. (Author's abstract)

116. Wilson, J. W. 1970. "Integration of Radar and Rain Gage Data for Improved Rainfall Measurement," *Journal of Applied Meteorology*, Vol 9, No. 3, pp 489-497.

Oklahoma thunderstorm data were used to determine how the estimation of area rainfall by radar can be improved by using one or several rain gages. The radar data were collected between 1964 and 1968 with the WSR-57 radar at the National Severe Storms Laboratory, Norman, OK. The rainfall data were obtained from the Agriculture Research Service's dense network of rain gages near Chickasha, OK.

The improvement of area rainfall measurements by combining radar measurements with discrete rain-gage measurements is demonstrated. It is shown, for example, that the rms error of radar measurements of storm rainfall amount, for a 1,000-mi^2 area, was reduced by 39% after the radar was calibrated with only one rain gage. At least four uniformly spaced gages are required to measure storm rainfall amounts for the same area as accurately as the radar calibrated with only one gage per 1,000 mi^2.

The ability of radar to measure rainfall variability accurately has been demonstrated; therefore, it is possible to assess objectively whether a particular gage measurement will be useful for adjusting radar rainfall measurements.

With the recent development of an effective system for automatically digitizing and communicating radar data in a form suitable for computer processing, these findings make possible the development of an operational system for measuring rainfall with an accuracy and timeliness never before achieved. (Author's abstract)

117. Wilson, J. W. 1975. "Measurement of Snowfall by Radar During the IFYGL," *Preprints: Sixteenth Conference on Radar Meteorology, American Meteorological Society, 22-24 April 1975, Seattle, WA*, pp 508-513.

Radar can be used to estimate water equivalents of snowfall with approximately the same accuracy as for rainfall; 80 to 90 percent of the radar estimates are within a factor of two of the gage measurements for radar ranges within 50 km. The maximum radar range of useful snowfall estimates is generally more limited than that for rainfall. It is believed this is a direct result of the relatively low level of precipitation growth in snowstorms. Because of this, non-uniform beam filling and over-shooting of the precipitation generally occur at closer ranges for snow than for rain. The accuracy of the radar estimates of snowfall varies with storm type, the highest accuracy occurs with large-scale storms where the primary snowfall production is above 2 km and the lowest accuracy occurring with "lake-effect" snowstorms that are characterized by small horizontal and vertical extent. There was evidence that spatial dendrite snow crystals predominate in "lake-effect" snowstorms and that these crystals give a higher reflectivity than others. It is important that an empirical range correction be made to the radar estimates of snowfall to adjust for non-uniform beam filling and different storm types.

Radar measurements of rainfall during the fall and winter indicated that at radar ranges where the beam intercepted the freezing level and became partially or completely filled by snow the radar underestimates the surface rainfall. Thus for cold season rainfall, it is desirable to make empirical range corrections to the radar precipitation estimates. These corrections should vary with the height of the freezing layer.

The root-mean-square error in the radar estimates can be reduced up to 50 percent through the use of a reference gage to adjust the radar snowfall estimate. The reduction depends on distance from the reference gage, geographical location, and storm type. It is felt that variations in the accuracy of the radar estimates are caused by variations in snow crystal type and degree of low-level snowfall growth. These factors are likely affected in an unkown manner by orographic lifting and moisture injection from the lake.

Because of the rapid changes in echo intensity with height during the cold season, it is particularly important for precipitation measurements during this season to keep the radar beam narrow and close to the ground. (Author's summary)

118. Wilson, J. W., and Brandes, E. A. 1979. "Radar Measurement of Rainfall-A Summary," *Bulletin of the American Meteorological Society*, Vol 60, No. 9, pp 1048-1058.

Radar can produce detailed precipitation information for large areas from a single location in real time. Although radar has been used experimentally for nearly 30 years to measure rainfall, operational implementation has been slow. Today we find that data are under-utilized and both confusion and misunderstanding exist about the inherent ability of radar to measure rainfall, about factors that contribute to errors, and about the importance of careful calibration and signal processing.

Areal and point rainfall estimates are often in error by a factor of two or more. Error sources reside in measurement of radar reflectivity factors, evaporation and advection of precipitation before reaching the ground, and variations in drop-size distribution and vertical air motions. Nevertheless, radar can be of lifesaving usefulness by alerting forecasters to the potential for flash flood.

The most successful technique for improving the radar rainfall estimates has been to "calibrate" the radar with rain gages. Simple techniques that combine sparse gage reports (one gage per 1,000-2,000 km^2) with radar produce smaller measurement errors (10-30%) than either system alone. When high-accuracy rainfall measurements are needed (average error less than about 10 to 20%) the advantage of radar is diminished since the number of gages required for calibration is itself sufficient to provide the desired accuracy. (Author's abstract)

119. Woodley, W., and Herndon, A. 1970. "A Rain Gage Evaluation of the Miami Reflectivity-Rainfall Rate Relation," *Journal of Applied Meteorology*, Vol 9, No. 1, pp 258-264.

To provide a foundation for other radar studies in the Miami area, 50 comparisons were made between shower rainfall recorded by rain gages and observed with radar to evaluate the reflectivity Z, rainfall rate R relation, $Z = 300R^{1.4}$, referred to here as the Miami Z-R relation. Total shower rainfalls measured by recording rain gages were compared with estimates derived from the Miami Z-R relation in conjunction with radar reflectivity measurements with iso-echo contouring and the analysis scheme described. Rainfall rate comparisons were not possible because of the poor time resolution of the rain gage observations. The radar and rain gage estimates of shower rainfall were highly correlated (+0.93, significant at the 1% level); they had an average difference of 8% and a mean absolute difference of 30%. Stratification by shower amount revealed that the radar estimate of gage-recorded rainfall was too high for small shower amounts (<0.25 in.) and too low for large shower amounts. In terms of percentage the comparison was best for the heavy showers. Stepwise regression analysis showed that consideration of the square of the range from gage to radar, in addition to range normalization already provided in the radar receiving system, made a small (3%) but statistically significant (<1% level) reduction in the variance and improved the correlation (0.93 to 0.944) between the gage and radar estimates of precipitation. It is concluded that the Miami Z-R relation, when used with the radar system described, is an effective tool in representing point and area rainfall from south Florida convective showers. (Author's abstract)

120. Woodley, W. L., Olsen, A. R., Herndon, A., and Wiggert, V. 1975. "Comparison of Gage and Radar Methods of Convective Rain Measurement," *Bulletin of the American Meteorological Society*, Vol 14, pp 909-928.

Gage and radar methods of convective rain measurements are compared in the context of the continuing multiple cloud-seeding experiment of the Experimental Meteorology Laboratory. An optimal system, combining the best features of both, is recommended.

The nature of the Florida convective rainfall to be measured is documented using measurements from a dense rain gage mesonet (about 3 km^2 per gage over 570 km^2) that was operated for a total of 93 days in 1971 and 1973, and the gaging requirements for detection and measurement of 24-hr rainfalls in the mesonet are determined using the full complement of gages as the standard. For the measurement of areal convective rainfall greater than 0.25 mm within a factor of 2 on 90, 70, and 50% of the days, gage densities of 31, 91, and 208 km^2 per gage, respectively, are required.

Radar performance in estimating convective rainfall over south Florida is determined using two colocated, calibrated 10-cm radars (UM/10-cm of the University of Miami and WSR-57 of the National Hurricane Center). In all cases, the radar estimates of rainfall are compared with the rainfall as determined by rain gages (densities 3 to 8 km^2 per gage) in cluster arrays. The relative performances of the two radars are compared.

In 1973, WSR-57 radar-derived rainfalls were computed by hand as in 1972 and by computer using taped radar observations. On a daily basis, 80% of the radar estimates were within a factor of 2 of the cluster standard. The combined accuracy of the WSR- 57 radar in 1972 and 1973 in estimating convective rainfall approximated that which one would obtain with a gage density of 65 km^2 per gage over an area the size of the mesonet.

The daily representation of rainfall by the radar improves if one adjusts it using gages. In the mean, adjustment produced a statistically significant 15% improvement (<1% level with two-tailed "t" test) in radar accuracy. The adjusted radar measurements then had an approximate gage density equivalence of 25 km^2 per gage.

The gaging requirements for the estimation of area mean rainfall for an area the size of the EML target (1.3×10^4 km^2) is inferred using the digitized radar observations. To meet a specification that the area mean rainfall be measured to within a factor of 2 of the true value 99% of the time requires 143 km^2 per gage, compared to a requirement of at least 13 km^2 per gage for the mesonet.

An optimum method of rain measurement is suggested. For the measurement of the rainfall from individual showers anywhere, the gage-adjusted radar is far superior to gages alone. For measurements in a fixed area the size of the mesonet, gages are superior to the radar. To measure rainfall over the EML target either gages alone or a radar adjusted by gages can accomplish the task. About 90 evenly spaced gages in the EML target should provide area rain measurements within a factor of 2 of the true value 99% of the time. The radar estimates adjusted by gages should be as accurate as those provided by the network cf 90 gages. The final choice as to the measurement system will probably be determined by other considerations such as budget, personnel, and the terrain over which the measurements are to be made. (Author's abstract)

121. Woodley, W. L., Griffith, C. G., Griffin, J. S., and Stromatt, S. C. 1980. "The Inference of GATE Convective Rainfall from SMS-1 Imagery," *Journal of Applied Meteorology*, Vol 19, No. 4, pp 388-408.

Quantitative precipitation estimates have been made for the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) from geosynchronous, infrared satellite imagery and a computer-automated technique that is described in this paper. Volumetric rain estimates were made for the GATE A scale (1.43×10^7 km^2) and for a 3-deg square (1.10×10^5 km^2) that enclosed the B scale for time frames ranging from all of GATE (27 June-20 September 1974) down to 6-hr segments. The estimates for the square are compared with independent rain measurements made by four C-band digital radars that were complemented by shipboard rain gages. The A-scale estimates were compared to rainfall estimates generated by NASA using Nimbus 5 microwave imagery. Other analyses presented include 1) comparisons of the satellite rain estimates over Africa with rain gage measurements, 2) maps of satellite-inferred locations and frequencies of new cumulonimbus cloud formation, mergers and dissipations, 3) latitudinal precipitation cross sections along several longitudes, and 4) diurnal rainfall patterns.

The satellite-generated B-scale rainfall patterning is similar to, and the rain volumes are within a factor of 1.10 of those provided by, radar for phases 1 and 3. The isohyetal patterns are similar in phase 2, but the satellite estimates are low, relative to the radar, by a factor of 1.73. The B-scale disparity in phase 2 is probably due to the existence of rather shallow but rain-productive convective clouds in the B scale. This disparity apparently does not carry over to the A scale in phase 2. Comparison of NASA Electronically Scanning Microwave Radiometer (ESMR) rain estimates with ours for several areas within the A scale for all GATE suggests that the former is low relative to the latter by a factor of 1.50. The satellite estimates of rainfall in Africa are similar to measurements by rain gages in all phases of GATE up to 11 deg N and progressively greater than the gage measurements north of this latitude toward the Sahara Desert.

The diurnal rainfall studies suggest a midday (about 1200 GMT) maximum of rainfall over the water areas and a late evening maximum (about 0000 GMT) over Africa and the northern part of South America. The latitudinal cross sections along several longitudes of phase rainfall clearly show the west-southwest/east-northeast orientation of the Intertropical Convergence Zone (ITCZ), the diminution of the rainfall west-southwest from Africa into the Atlantic, and the northward progression of the ITCZ from phase 1 into phases 2 and 3. The center of action for cloud formation, merger and dissipation, and the area of maximum rainfall (1,600 mm for all of GATE) occur along the southwest African coast near 11^{o} N. This agrees with past climatologies for this region. Superposition of the satellite-generated rainfall maps and sea surface temperature maps by phase suggest a strong relationship between the two. Almost all of the rainfall occurs within a 26^{o} C sea surface temperature envelope. The mean daily coverage of rainfall and the mean rainfall in the raining areas for the A scale for all GATE are 20% and 14.1 mm day^{-1}, respectively. These and other results are discussed. (Author's abstract)

122. Yau, M. K., and Rodgers, R. R. 1983. "Approximate Method for Converting Rainfall Duration Distributions to Area Distributions," *Preprints: Twenty-first Conference on Radar Meteorology, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 713-718.

Our study has shown that statistics on the areal extent of rainfall can be determined from point-rainfall measurements. The accuracy of the inversion technique was confirmed using radar data adjusted for the bias against small echoes. It seems likely that the technique can be applied to most mid-latitude locations, where precipitation patterns move relatively fast and are not strongly influenced by orographic effects. It would be useful to carry out the analysis for other sites where sufficient radar data exist for a comparison. (Author's summary)

123. Zawadzki, I. 1975. "On Radar-Rain Gage Comparison," *Journal of Applied Meteorology*, Vol 14, No. 8, pp 1430-1436.

Special smoothing by the radar beam as well as post-detection integration reduce the variability of the distribution of rainfall rate in space. It is shown that when radar data are compared with the instantaneous point rainfall rate, a random error and a bias are introduced by the smoothing. This could account for some of the difficulties in the hydrological use of radars. It is shown that when rain gage data are smoothed in time there is an optimum smoothing time interval such that the random error and the bias are reduced to a negligible level. A method is suggested for the optimum comparison of radar and rain gage data and the possibility of a determination of a Z-R relationship from such comparisons is discussed. (Author's abstract)

124. Zawadzki, I. 1984. "Factors Affecting the Precision of Radar Measurements of Rain," *Preprints: Twenty-second Conference on Radar Meteorology, 10-13 September 1984, Zurich, Switzerland*, pp 251-256.

A great deal of effort has been made to account for the variability of the drop-size spectra: real-time calibration with one (or more) gages, dual wavelength, polarization diversity, and a great care in deriving Z-R relationships from drop spectra measured at the ground.

The analysis presented here shows that, from the point of view of precipitation measurements at ground, the variability of drop-size spectra introduces one of many errors and not the most severe at that. Even if some of the above-mentioned techniques succeed in determining precisely the drop-size distribution within the "illuminated volume," the improvement in rain measurements at ground is not likely to be great.

Real-time calibration of the radar with a rain gage, although an attractive idea in principle, may introduce as many problems as solutions: if the calibration is made in regions where biases due to nonuniformity of the precipitation field are severe, the whole rain rate pattern will be estimated with additional (and severe) errors. The same effect will be introduced by horizontal advection and by attenuation (whenever present). Calibrating with a gage may have the effect of uncalibrating the radar entirely, particularly in cellular rain patterns.

Reflectivity-rain gage relationships obtained by radar-rain gage comparison (in probability or by regression) will compensate on the average all the error if enough data are used in the comparison. Range effects can be compensated for by statistics of reflectivity as a function of range such as described by Calheiros and Zawakzki (1983). However, these techniques will not eliminate the large scatter of individual measurements of rain rate. The accuracy of radar estimates of precipitation at ground will only be improved by addressing the various sources of error in a painstaking and a meticulous manner. The combination of hardware and software made available by the technology of today permits a complexity of radar data processing which should be helpful in reducing the errors discussed here. (Author's summary)

APPENDIX B: ANNOTATED BIBLIOGRAPHY OF SHORT-TERM WEATHER FORECASTING AND RECENT DEVELOPMENTS IN RADAR METEOROLOGY

1. Ahnert, P. R., Hudlow, M. D., Johnson, E. R., Greene, D. R., and Dias, M. P. R. 1983. "Proposed 'On-Site' Precipitation Processing System for NEXRAD," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada,* pp 378-385.

   This paper describes five algorithms employed in the "on-site" analysis of precipitation in the NEXRAD system. Emphasis is placed on reflectivity data inputs, hybrid scan construction, conversion to rainfall rate, temporal continuity tests, range effects, and periods of accumulation. Also included in the discussion is the need for gage-radar adjustments.

   Product generation includes data sets for "off-site" processing as well as an hourly precipitation product which provides an hourly running total and is updated approximately every 5 min. This graphic will be displayed on a 2 km by 2 km grid out to 230 km. Other products include a 3-hr precipitation map and a storm total precipitation map.

   Limitations and possible future developments are discussed. (Author's summary)

2. Ahnert, P., Hudlow, M., and Johnson, E. R. 1984. "Validation of the 'On-Site' Precipitation Processing System for NEXRAD," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland,* pp 192-201.

   The algorithm specifications as currently stated performed very well except in mountainous terrain where a modification to the original design to use a sectionized hybrid approach will improve the performance significantly. Based on the 5-1/4-hr case study, an initial set of parameters can now be specified. Tests indicate that round-off and truncation errors may require internal storage of dBR values to a precision greater than the currently specified 0.5 dBR. The four lowest tilts are needed once each 5 min during times of precipitation.

   With the completion of the real data tests on the rain gage adjustment procedure and a few additional refinements to the code to optimize the performance and computer efficiency, the algorithms will be ready for implementation as a real-time processing system. Final testing and documentation for this system is scheduled for completion by August 31, 1984. At that time efforts will be directed toward extension of the NEXRAD applications software development work to include a Flash Flood Alert Algorithm. The Flash Flood Alert Algorithm will use as its primary input the rainfall estimates from the "On-Site" Precipitation Processing System and will incorporate simple hydrologic and pattern extrapolation to identify areas of flash flood potential. (Author's summary)

3. Austin, G. L., and Bellon, A. 1974. "The Use of Digital Weather Radar Records for Short-Term Precipitation Forecasting," *Quarterly Journal of the Royal Meteorological Society*, Vol 100, pp 658-664.

Weather radar may be used for forecasting the motion and development of precipitation patterns. A technique is described here which uses digital data sets and a computer pattern-matching programme to forecast storm motion for periods between one-half and 2 or 3 hr. The technique is able to track systems as they appear over the edge of the display by locking on to the leading edge features. Considerable attention has been given to evaluation techniques, and more than 30 experiments involving seven different days of data from radars in Toronto and Montreal have been performed. It was found that although different classes of events had different forecastabilities, it was possible to obtain useful results for 1-hr forecasts on all the events studied. (Author's abstract)

4. Ball, A., Clarke, J. L., Davy, B. D., O'Brien, M. J., Trigg, S. E., Taylor, B. C., and Voller, T. A. 1975. *A System for the Processing, Transmission and Remote Display of Data from a Weather Radar*, Royal Signals and Radar Establishment Memorandum No. 3032, Malvern, England, p 40.

The memo describes a prototype system which has been developed to enable quantitative precipitation data from a weather radar to be made available in timely fashion to meteorologists and hydrologists remote from the radar station. The data is available within 30 sec of its acquisition by the radar and is presented as a colour-coded map showing the intensity distribution of the rainfall over a large area. The display terminal uses a modified colour television set and the transmission is by means of standard PO lines. Other data outputs are available in a computer-compatible format, and the system design is such as to allow future expansion to embrace a number of radars and to meet a number of different user requirements.

An experimental system has been implemented at a radar site in North Wales and is currently transmitting instantaneous rainfall 'pictures' and integrated rainfall totals to the Meteorological Office at Preston, to the Malvern Office of the Severn-Trent Regional Water Authority, and to the Bala Office of the Welsh National Water Development Authority. (Author's summary)

5. Bellon, A., and Austin, G. L. 1977. "The Real Time Test and Evaluation of SHARP, a Short Term Precipitation Forecasting Procedure," McGill University, Stormy Weather Group, Final Report for Atmospheric Environment Service, Montreal, Canada, p 57.

SHARP operated successfully for 1,036 hours between June 1st and September 20, 1976. During that period, dependable forecasts in the form of 3-km CAPPI maps, followed by specific station forecasts, were issued to a remote weather office. These forecasts closely approach the optimum accuracy that can be attained under the "status quo" assumption. Verification of these forecasts with observed

data allowed determination of preferred regions of storm development and decay. (Author's abstract)

6. Bellon, A., and Austin, G. L. 1978. "The Evaluation of Two Years of Real-Time Operation of a Short-Term Precipitation Forecasting Procedure (SHARP)," *Journal of Applied Meteorology*, Vol 17, No. 12, pp 1778-1787.

   Digital weather radar data have been used with a simple pattern recognition procedure to automatically generate precipitation forecasts in the 0- to 3-hour range. Such a technique has been in a real-time operation for two years. The verification of the procedure has led to a preliminary "radar climatology" for the Montreal area in the form of a map of areas showing a predominant growth or decay of precipitation patterns. (Author's abstract)

7. Bellon, A., and Austin, G. L. 1978. "The Real Time Test and Evaluation of 'Sharp': A Short Term Precipitation Forecasting Procedure," *Preprints: Eighteenth Conference on Radar Meteorology, American Meteorological Society, 28-31 March 1978, Atlanta, GA*, pp 478-483.

   It is believed that the original aims of the SHARP project were fully accomplished during the first real-time test and were confirmed in the second year of operation. Moreover, the by-products of the test and results from the analysis of the forecasts yielded new scientific information concerning the handling and potential of digital radar data.

   1. The system operated successfully for 1,036 hours during the period between June 1 and September 20, 1976. This performance is equivalent to a reliability of 85 percent.
   2. Dependable forecasts in the form of 3-km CAPPI maps followed by specific station forecasts were issued to a remote weather office. The consensus of the personnel receiving the output supported the usefulness of the products particularly in severe weather and provided stimulating suggestions concerning the improvement and expansion of the present format, most of which were implemented in the 1977 version of the test.
   3. Analysis of these forecasts revealed that they represent nearly the best accuracy that can be attained under the "status quo" assumption.
   4. Potentially erroneous forecasts due to anomalous propagation and gross matching errors were correctly rejected by the computer according to predetermined criteria.
   5. Additional products in the form of ETPPI and hydrological maps were also transmitted to the weather office as a preview of the many facets of digital radar data.

6. The large amount of data collected during the test permitted the determination of preferred regions of storm development and decay, a first step into radar climatology.
7. A SHARP procedure operating on 2-km CAPPI's suitable for low weather or winter storms has also been devised. (Author's summary)

8. Bellon, A., and Kilambi, A. 1980. "Automated System for Short Range Precipitation Forecasting Using Combined Radar and Satellite," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL,* pp 66-71.

An extension of the SHARP program to include precipitation probability maps incorporating images obtained from SMS/GOES-E satellites. A review of three case studies is included. Recommendations include immediate implementation of the prototype procedure into real-time continuous operation. (Author's summary)

9. Bellon, A., and Austin, G. L. 1984. "The Accuracy of Short-term Radar Rainfall Forecasts," *Journal of Hydrology,* Vol 70, No. 1, pp 35-49.

A total of 37 weather sequences which passed over the city of Montreal, Quebec, Canada, and which were observed by radar, have been analysed. The object was to determine the accuracy of simple forecasting schemes in giving estimates of the amount of rain an hour or two ahead. Verification was achieved using data from a network of telemetered gages. It was found that the radar-measured accumulations have an inherent error of the order of 25 percent, 0.5-hr forecasts have an error of ~ 50 percent and 3-hr forecasts have an error of ~60 percent. (Author's abstract)

10. Bergwall, F., Humphries, R. G., and Strong, G. S. 1983. "The Use of Radar and a Convective Index for 1-6 Hour Regional Forecasts," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada,* pp 371-374.

A regional predictor of potential convection, the Synoptic Index (SC4) has been developed for the Alberta Research Council Hail Project (AHP). The SC4 combines four predictor variables: 1) EGDEX, a lifted index, modified for wind direction and diurnal heating, 2) the Surface Parcel Lifted Index, 3) the 24-hour, 700-mb* temperature change, and 4) the 24-hour, 1,000- to 500-mb thickness change. The SC4 is statistically correlated to predictand, the Convective Day Category (CDC), as defined in the paper. The resultant maps of potential convective instability make it possible to forecast probable storm development regions and areas of the most intense convection.

Radar data used in conjunction with the SC4 regional convective forecasts and the moisture field, represented by equivalent potential temperature, demonstrate how radar data can be used to produce 1- to 6-hr forecasts of storm evolution and motion. The SC4 provides a realistic forecast of the region of maximum convection. Large convective complexes, clusters of storms which may not be physically connected and are less than 100 km apart, tend to propagate along the orientation of the SC4 field, reaching peak intensity near the surface equivalent potential temperature maximum. Two case studies are presented. One, 21 July 1979, represents severe convective activity and the other, 23 August 1979, represents light to moderate convection. (Author's summary)

11. Bonewitz, J. D. 1981. "The NEXRAD Program—An Overview," *Preprints: Twentieth Conference on Radar Meteorology, American Meteorological Society, 30 Nov-3 Dec 1981, Boston, MA*, pp 757-761.

    As a major upgrading of existing weather radar capability, the NEXRAD System will improve the detection of potentially hazardous weather phenomena and reduce the number of false alarms. This should produce a significant improvement in warnings of severe weather with the resultant savings to the government and the public.

    NEXRAD is a joint agency effort to provide service to the nation in an efficient and cost-effective manner. Program strategy involves the JSPO, Government laboratories, universities, and private industry.

    Perhaps the most significant feature within the NEXRAD program is that three departments of the Federal government are developing a single national system—one that will best serve the needs of the country, while attempting to minimize life cycle costs. While NEXRAD cannot hope to be all things to all people, there is hope that this program will produce a truly national weather radar system. (Author's summary)

12. Browning, K. A. 1979. "The FRONTIERS Plan: A Strategy for Using Radar and Satellite Imagery for Very-Short-Range Precipitation Forecasting," *The Meteorological Magazine*, Vol 108, No. 1283, pp 161-183.

    The FRONTIERS program described in this article addresses the problem of analysing and forecasting the detailed pattern of precipitation over the period 0-6 hr ahead. The acronym FRONTIERS embodies the following key elements: Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite. In this program we adopt a whole-system design approach, with digital data handling all the way from the observational input to the disseminated forecast product. We also emphasize the crucial role of human judgement which is required to make up for the limitations of the observational data and the incompleteness of our understanding on the mesoscale. In the plan discussed here, the data from a network of radars and a geostationary satellite are composited on an interactive video display, and the forecaster does his analysis and forecasting by modifying what is on the television screen while preserving the basic data in store. The resulting screenful of digital information can then be tailored and disseminated promptly to users without further manual effort. Although the emphasis in this paper is on the accurate analysis of current weather

and extrapolation of current trends, these methods must be considered in the context of an eventual forecast system incorporating a mesoscale numerical model. (Author's summary)

13. Browning, K. A. 1980. "Radar as Part of an Integrated System for Measuring and Forecasting Rain in the UK: Progress and Plans," *Weather*, Vol 35, No. 1, pp 94-104.

This article is a review of past and current weather radar projects in the United Kingdom. Special attention is focused on the Short Period Weather Forecasting Pilot Project.

14. Browning, K. A., Collier, C. G., Larke, P. R., Menmuir, P., Monk, G. A., and Owens, R. G. 1982. "On the Forecasting of Frontal Rain Using a Weather Radar Network," *Monthly Weather Review*, Vol 110, No. 6, pp 534-551.

This paper is concerned with the quantitative forecasting of hourly rainfall for the period 0-6 hr ahead using linear extrapolation techniques. It deals with results obtained as part of the Meteorological Office Short Period Forecasting Pilot Project. The primary data used in this study are composite maps of rainfall echo distribution generated automatically and in real time using digital data received from a network of four weather radars covering parts of England and Wales. Forecasts have been derived during a total of 29 frontal rainfall events between November 1979 and June 1980. The forecasts were derived both subjectively in real-time and objectively using a computerized echo centroid tracking technique. The objective procedure which was used to derive forecasts on a 32 by 32, 20-km^2 grid, is a practical way of quickly producing detailed forecasts for a large number of target areas, but its accuracy suffers from a number of factors. The subjective procedure, which was applied to a single target zone, was used to investigate some of the sources of error and their impact on forecasts. It is shown that radar rainfall measurement errors accounted for as much as half of the errors in the forecasts, and it is suggested that the biggest improvements in forecast accuracy are likely to accrue from improved analysis of the radar data prior to input into the forecast procedure. The radar measurement errors are due more to the variability of echo intensity with height than to straightforward radar calibration difficulties. Subtle procedures are required to identify these errors based on an analysis of the meteorological situation in which the radar data are viewed in the context of other kinds of meteorological information. Factors such as the development and decay of rainfall systems, which lead to the breakdown of the basic assumption underlying the linear extrapolation approach, accounted for about a quarter of the errors in the forecasts. (Author's abstract)

15. Browning, K. A., Carpenter, K. M., and Collier, C. G. 1983. "The Establishment of a System for the Operational Use of Weather Radar in the UK: A Status Report," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada,* pp 369-370.

The UK weather radar network is being developed as part of an integrated nowcasting system. This paper provides an overview of the system in headline format; references are given to enable the interested reader to pursue aspects in detail. (Author's summary)

16. Brunkow, D. A. 1980. "A Digital Radar-based Rainfall Monitoring and Forecasting Tool," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL*, pp 62-65.

    This paper describes work by the Illinois Water Survey on the Chicago Hydrometeorological Area Project during the summer of 1979. Included in the discussion is a review of the five software packages, DATA COLLECTION, CELL TRACKING, FORECAST, TOTAL, and EDITOR that are used in the program. The performance of the programs during the 1979 operational period indicated that an automated version of the cell tracking routine which would run every 5 min could be implemented. This would reduce the operator interaction to once every half hour. However, the current rainfall monitoring and forecasting system made considerable demands on the human operator. While the forecast technique was quantitative and objective, there were many opportunities for the operator to exert subjective influences. Therefore, the system should be viewed more as a tool to assist the meteorologist than as an automated forecasting system.

17. Collier, C. G. 1980. "Data Processing in the Meteorological Office Short-period Weather Forecasting Pilot Project," *The Meteorological Magazine*, Vol 109, No. 1295, pp 161-176.

    The Meteorological Office Short-period Weather Forecasting Pilot Project, which began in 1978, required the development of techniques for processing radar and satellite imagery. In this paper the data-processing system is described which enables data from several radars to be combined with data from Meteosat to give the mesoscale pattern of precipitation. The resulting data are presented within a minicomputer environment to small teams of research meteorologists and forecasters. The system is structured as a distributed processing minicomputer network mostly using dedicated communications lines rented from the Post Office. Instantaneous fields of precipitation, and rainfall totals integrated for short time periods over areas defined by users, are distributed from each radar site to a number of Meteorological Office and Water Authority users, who are at present assessing the usefulness of the data for real-time operations. The software modules which are used in this system are discussed and the data archives which are being created are described. (Author's summary)

18. Greene, D. R., Hudlow, M. D., and Johnson, E. R. 1980. "A Test of Some Objective Analysis Procedures for Merging Radar and Rain-Gage Data," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL*, pp 470-479.

This paper describes the work done by the Hydrologic Research Laboratory in the development of the Hydrologic Rainfall Analysis Project (HRAP). One of the major goals of the study was the evaluation of the Brandes (1975) and Crawford (1978) models for merging radar and raingage data. An outgrowth of HRAP is the recognition of the need for preliminary processing of data at the radar site with a minicomputer. This processing will include anomalous propagation discrimination and real-time quality control to identify any systemic bias in the radar-rainfall estimates. After the on-site preprocessing, the radar-rainfall estimates will be transmitted to a central site, having large-scale data processing capabilities, where radar-rainfall estimates are collected from multiple sites.

19. Greene, D. R., Nilsen, J. D., Saffle, R. E., Holmes, D. W., Hudlow, M. D., and Ahnert, P. R. 1983. "RADAP II, An Interim Radar Data Processor," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 404-408.

The National Weather Service (NWS) presently has a primary radar network of 51 WSR-57 and 5 WSR-74S weather radars. Supplemented by a number of WSR-74C local warning radars, this network provides nearly blanket radar coverage over the eastern two thirds of the United States. The full potential of the operational application of data from these weather radars has been limited because the data from most of these sites are presented to the user in video output form that requires manual processing if the data are to be used numerically to derive quantitative estimates. Faced with these shortcomings in the real-time quantitative application of radar data, the NWS began the Digitized Radar Experiment (D/RADEX) in 1971 with the goal of using automatic computer processing to enhance the usefulness of radar data. In D/RADEX, selected network WSR-57 radars were equipped with digitizing hardware including a mini computer, and programs were developed to process the digital data into various products having applications to both meteorology and hydrology.

In 1976, when the experiment officially ended, the NWS decided to convert the D/RADEX sites from experimental to quasi-operational status and to run in this mode as long as spare parts and available maintenance would allow. At present, four of the five D/RADEX sites are still operational. These sites are Kansas City, MO, Monett, MO, Oklahoma City, OK, and Pittsburgh, PA. In the summer of 1981, a new WSR-74S radar equipped with a D/RADEX type processor was installed at Jackson, KY. (Author's summary)

20. Hudlow, M. D., Greene, D. R., Ahnert, P. R., Krajewski, W. F., Sivaramakrishnan, T. R., Johnson, E. R., and Dias, M. R. 1983. "Proposed Off-site Precipitation Processing System for NEXRAD," *Preprints: Twenty-first Conference on Radar Meteorology, American Meteorological Society, 19-23 September 1983, Edmonton, Alberta, Canada*, pp 394-403.

This paper outlines the Stage II processing system for the NEXRAD network. Included in the discussions are descriptions of the zero precipitation and outlier quality control checks,quality control decision tree, mean field bias elimination techniques, mosaicking, and precipitation data distribution and use.

21. Hudlow, M. D., Farnsworth, R. K., and Ahnert, P. R. 1985. *NEXRAD Technical Requirements for Precipitation Estimation and Accompanying Economic Benefits*, Hydro Technical Note 4, Hydrology Research Laboratory, National Weather Service, National Oceanic and Atmospheric Administration, Silver Springs, MD, p 49.

A technical requirements and economic benefits study was initiated to demonstrate how the precipitation estimation capability of the Next Generation Weather Radar (NEXRAD) would benefit the nation, and how these potential benefits would be impacted if the technical characteristics, as currently planned for the NEXRAD systems, were relaxed to save some capital equipment costs. Although there are many general areas of economic benefit, including those related to aviation and general weather forecasting and severe storm and hurricane warnings, only those benefits derived from improved precipitation estimates for input to real-time hydrologic forecast procedures are addressed in this study. (Author's summary)

22. Huff, F. A., and Changnon, S. A., Jr. 1977. "A Hydrometeorological Research Program," *Water Resources Bulletin*, Vol 13, No. 3, pp 574-581.

An extensive research program in hydrometeorology was recently initiated in the Chicago region. Major objectives are to 1) develop a real-time, prediction-monitoring system for storm rainfall using a combination of weather radar and telemetered rain gage data, 2) determine precipitation measurement requirements for hydrologic design, operation, and modeling purposes, 3) define the time-space characteristics of heavy rainstorms in the Chicago urban area, and 4) establish methods for applying the Chicago findings in other cities. Basic components of the field measurement program are a network of over 300 recording rain gages in 4,000 square miles in and around Chicago, plus two sophisticated weather radar systems for obtaining real-time information on storm parameters pertinent to optimizing operation of urban water resources systems. The rain gage networks are to be used to compile information relevant to both design and operational aspects of urban hydrology. Radars are to be used primarily in developing the real-time operational techniques. Testing and evaluation of the real-time operational system will be done in cooperation with the Metropolitan Sanitary District of Chicago, operator of one of the most complex urban water control systems among major metropolitan areas. (Author's abstract)

23. Huff, F. A., and Towery, N. G. 1978. "Utilization of Radar in Operation of Urban Hydrologic Systems," *Preprints: Eighteenth Conference on Radar Meteorology, American Meteorological Society, 28-31 March 1978, Atlanta, GA*, pp 437-441.

An extensive research program in hydrometeorology was initiated in early 1976 in the Chicago region. Major objectives are to 1) develop a real-time, prediction-monitoring system for storm rainfall using a combination of weather radar and telemetered raingage data, 2) determine precipitation measurement requirements for hydrologic design, operation, and modeling purposes, 3) define the time-space characteristics of heavy rainstorms in the Chicago urban area, and 4) establish methods for applying the Chicago findings in other cities. Basic components of the field measurement program are a network of 320 recording raingages in 10,000 km^2 in and around Chicago, plus two sophisticated weather radar systems for obtaining real-time information on storm parameters pertinent to optimizing operation of urban water resources systems. The rain gage networks are used to compile information relevant to both design and operational aspects of urban hydrology. The radars are used primarily in developing the real-time operational techniques. Testing and evaluation of the real-time operational system is being done in cooperation with the Metropolitan Sanitary District (MSD) of Chicago, operator of one of the most complex urban water control systems among major metropolitan areas. This paper is limited to discussion of the first objective listed above. (Author's summary)

24. Huff, F. A., Changnon, S. A., and Vogel, J. L. 1980. "Convective Rain Monitoring and Forecasting System for an Urban Area," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL*, pp 56-61.

A dense rain gage network and radar system were operated during the summers of 1976 and 1977 in the Chicago area to test the feasibility of using a radar-rain gage mix to measure and predict quantitative storm rainfall in summer convective conditions. Techniques for the real-time monitoring and forecast of summer convective activity were developed, tested, adopted, and demonstrated.

Preliminary analysis of the forecasting schemes indicated that as rainfall approaches an urban region, the accuracy of the radar-determined rain rate should increase. For example, it is sufficient to monitor precipitation systems more than 35 km away from the urban region using a climatic-derived and adjusted Z-R equation. However, as the storms begin to move toward the city, increasingly more accurate determinations of the rain rate are necessary. Thus, the density of telemetered rain gages should maximize over the urban region. For warm season convective rainfall, it is recommended that the rain gage density at 30 to 35 km from the city be 1 gage per 250 to 300 km^2, and the gage density in the city should be 1 gage per 60 to 120 km^2.

A demonstration of the real-time capabilities of the radar-man system was given during the summer of 1979. Preliminary results from a storm on 30 July 1979 suggest that for such heavier, or hydrologically significant, rains, the system was able to monitor areal rainfall averages to within 13% of the total storm rainfall. Further, the average error of the 30-minute accumulated storm rainfall amounts

greater than 2 mm ranged from 13 to 20%. The radar-man forecast technique was able to predict the onset of precipitation within 30 min. The 30-min updated forecasts of urban rain amounts for 30, 60, and 120 min ahead had average forecast errors which ranged from 3 to 5 mm. No adjustments had to be made to the radar-indicated rainfall amounts, and all estimates were based on the climatically derived CHAP Z-R relation. However, preliminary analysis of other storms indicates the necessity for adjusting the radar-indicated rainfall values for both monitoring and forecasting purposes. Results from the demonstration stress the need to employ skilled operators including an experienced radar meteorologist to effectively utilize radar as a heavy rainfall prediction tool. (Author's summary)

25. Huff, F. A., Vogel, J. L., and Changnon, S. A., Jr. 1981. "Real-time Rainfall Monitoring—Prediction System and Urban Hydrologic Operations," *Journal of the Water Resources Planning and Management Division, Proceedings of the American Society of Civil Engineers*, Vol 107, No. 2, pp 419-435.

    A major-objective 4-year study was conducted in the Chicago region. It involved the development of a real-time monitoring/prediction system utilizing a combination of weather radar and telemetered recording rain gage data. Monitoring of rainfall from storms approaching and crossing the urban area, and predicting the rainfall distribution over the urban area for the upcoming 30 min, 60 min, and 120 min were the two basic goals of the research.

    Research indicated that the rain monitoring accuracy of the man-machine combination was definitely superior to that obtained with unadjusted radar-rainfall measurements, and was equivalent, if not slightly superior, to the measurements made by the relatively dense network of recording rain gages.

    Evaluation of the forecasting success with the man-machine combination provided strong support for the applicability of the prediction-monitoring system to real-time operational problems in urban areas. The man-machine mix was proven superior to radar alone in providing short-term forecasts and was some 18 to 32% better for individual and accumulative forecasts of 0.2 in. (5.0 mm) or greater during the 2-month demonstration period.

    Both monitoring and prediction information proved useful to the Metropolitan Sanitary District during the demonstration period. Accuracy levels were achieved that were sufficient to facilitate and improve the operational efficiency of urban systems.

    Recommendations included the use of satellite imagery to serve as a guide to alerting operational personnel to the expected characteristics of incoming, large-scale storm systems. (Author's summary)

26. *Next Generation Weather Radar Algorithm Report*. 1984. The NEXRAD Joint System Program Office.

A basic requirement for the design of the NEXRAD system is the automation of meteorological and hydrological analyses. This report represents the algorithms being developed to satisfy this requirement.

While this report represents the current (1984) status of NEXRAD algorithms, it is recognized that improvements, modifications, corrections, etc., remain to be made. During the life of the NEXRAD system (from acquisition through operational use), the government expects to modify the algorithms defined in this report and to develop new algorithms. The full benefits of the NEXRAD system can be realized only through this process of enhancement. Thus, the design of the NEXRAD system must allow for the modification, addition, and deletion of algorithms. In this way the Government expects the NEXRAD system to keep pace with future advancements in the processing of weather radar data. (Report's preface)

27. O'Bannon, T., and Ahnert, P. 1986. "A Study of the NEXRAD Precipitation Processing System on a Winter-type Oklahoma Rainstorm," *Preprints: Twenty-third Conference on Radar Meteorology, American Meteorological Society 22-26 September 1986, Snowmass, CO.*

The Next Generation Weather Radar (NEXRAD) "on-site" Precipitation Processing System (PPS) was developed by the Hydrologic Research Laboratory (HRL) of the National Weather Service (NWS) to provide accurate and reliable rainfall estimates for the conterminous United States from a network of more than 100 high-resolution 10-cm radars. The PPS is described in detail by Ahnert el al. (1983) and a complete functional specification is contained in the NEXRAD Algorithm Report (1985). The radar-estimated rainfall is to be adjusted for mean field bias in real-time using a number of telemetered rain gage reports. Adjusted rainfall values will be available as NEXRAD graphics products and as a high-resolution (100 data level, approximately 4 km by 4 km) data array product for input to flash flood and river forecast models and procedures.

A report on the validation of the NEXRAD PPS using radar and gage data from a Colorado thunderstorm event was presented at the 22nd AMS Radar Conference (Ahnert et al. 1984). Further validation on other data sets was recommended by the NEXRAD Joint Systems Program Office (JSPO) in order to determine the performance of the Kalman filter bias adjustment and the effect of certain algorithm adaptable parameter changes in different weather regimes. This paper presents the results of tests on an Oklahoma winter rain event. (Author's summary)

28. Saffle, R. E. 1976. "D/RADEX Products and Field Operations," *Preprints: Seventeenth Conference on Radar Meteorology, American Meteorological Society, 26-29 October 1976, Seattle, WA*, pp 555-559.

D/RADEX has taken some large steps toward utilizing the information potential of weather radars. We now know that we can process the large volumes of data in real-time, we can share the radar with a human operator, and we can develop products that would be impossible for the human operator to duplicate. One of the encouraging aspects of these developments is that the DROS software concepts have proven extremely adaptable to different hardware configurations and to experimentation with new products. This software adaptability should be very valuable in RADAP. Under RADAP, input radar intensity data from a digital VIP (DVIP) will be linked with data from a signal variability processor (SVP). The SVP data will be values from 0 to 255 decimal, where higher SVP values indicate higher probability that the associated intensity value is rainfall (as opposed to ground clutter or anomalous propagation). With SVP data available, DROS rainfall estimates will be much less contaminated by non-rainfall echoes. Using the DVIP, a program could ask for data to be integrated over as small an area as 1 km by 1 deg. These high-resolution data could then be used to investigate particular thunderstorm cells in great detail. Another hardware development yet to be utilized in a DROS-type environment is Doppler radar. These examples illustrate how new hardware and imaginative software will be used to extract more, useful meteorological products from weather radars. (Author's summary)

29. Saffle, R. E., and Greene, D. R. 1978. "The Role of Radar in the Flash Flood Watch Warning System: Johnstown Examined," *Preprints: Eighteenth Conference on Radar Meteorology, American Meteorological Society, 26-31 March 1978, Atlanta, GA*, pp 468-473.

Although radar underestimated the maximum rainfall in comparison with rain gage measurements, radar estimates gave excellent definition of the time and space distributions of the rainfall and indicated several points of very heavy accumulations. Further, radar rainfall estimates were the only available indication of the flood potential of this event. According to the National Disaster Survey Report on Johnstown (National Oceanic and Atmospheric Administration 1977), real-time surface precipitation reports were not available due to the paucity of gages in the area of heavy rain and to communication problems with the gages that were within the area.

Several factors can contribute to errors in estimation of rainfall by the D/RADEX system:

(a) Time and space variations of the reflectivity/rainfall rate relationship. D/RADEX can compute many parameters (VIL, height of echo tops, variance of the reflectivity pattern, size of echoes, etc.) from the basic digitized radar data. Research currently being conducted in the NWS aims to identify parameters such as these that can be used to improve the rainfall rate estimation. Other research aims at adjusting radar rainfall estimates on the basis of rain gage data.

(b) Lack of sufficient reflectivity resolution in the 9 D/RADEX levels. As indicated in the paper D/RADEX 5 spans a 1.2-in./hr category and level 7, a 2.59-in./hr category. Since D/RADEX uses a rainfall range based on the midpoint of each category, it is clear that significant rate estimation errors for particular storms can result. We recommend that D/RADEX add more reflectivity resolution levels to minimize this source of error.

(c) The averaging of rainfall of 3 nautical miles by 5 nautical miles grid boxes. In convective rainfall cases, the average value of the grid box can be significantly less than the peak rainfall within the box. Figures in the paper demonstrated that some grid boxes with average rainfall values of 6 in. had peak values of 8 in. We recommend that D/RADEX add a product that estimates rainfall on a finer spatial resolution than the present 3 nautical miles by 5 nautical miles. (Author's summary)

30. Shreeve, K. H. 1980. "***RADAP***," *Preprints: Nineteenth Conference on Radar Meteorology, American Meteorological Society, 15-18 April 1980, Miami Beach, FL,* pp 76-79.

Within the last 10 years technology has made it economically practical to apply computer technology in the collection, processing, display, and communication of radar information. This was a very significant milestone, since it removed the human analysis restriction that has prevented the full value extraction of meteorological and hydrological information contained in weather radar data. During this time, a number of research organizations have implemented computers for this purpose. The National Weather Service started project "D/RADEX" (Saffle 1976) as a developmental effort to test the utility and improvements provided by a computer-driven data collection and processing system. Based on D/RADEX experiments and research conducted at the National Severe Storm Laboratory, the National Weather Service started the RAdar DAta Processor (RADAP) program. This program will provide a powerful computer system as an operational tool at many of the NWS primary weather radar sites. The RADAP system is designed for automated collection, processing, display and communications. An overview of the RADAP system's initial operational and expansion capabilities is given in the following paragraphs. (Author's summary)

31. Smart, J. R., and Alberty, R. L. 1984. "An Evaluation of the Performance of the NEXRAD Hail Algorithm," *Preprints: Twenty-second Conference on Radar Meteorology, American Meteorological Society, 10-13 September 1984, Zurich, Switzerland,* pp 202-207.

This study has presented preliminary findings regarding performance of the NEXRAD Hail Algorithm. When cells are not correctly identified, the Hail Algorithm cannot be applied. Investigations did suggest techniques that could improve storm identification. Although the Hail Algorithm was not specifically designed for high plains hailstorms, the results for the 39 events investigated indicate skill in identification of hail-producing thunderstorms (89.7% either positive or probable hail producers), provided cell identification itself was correct. Only four events, which showed "non-classic" structure, were labeled as not hail-producing. Refinements to accommodate some of the deficiencies noted may result in improved algorithm performance. As a result of these tests and similar testing by the NEXRAD Interim Operational Test Facility, some significant changes have

been made to the Hail Algorithm; in particular, the thresholds and assigned weights have been made adaptable parameters that can be easily changed for varying sites and seasons. (Author's summary)

32. Taylor, B. C., and Browning, K. A. 1974. "Towards an Automated Weather Radar Network," *Weather*, Vol 29, No. 6, pp 202-216.

This paper is a review of the work being undertaken at the Royal Radar Establishment, Malvern, England, to design an automated weather radar network which is suitable for meteorological research and which is also suitable for hydrological and forecasting uses. The work began in 1970 with a paper study which envisaged an eventual National Weather Radar Network, consisting of a number of interlinked unmanned radars. This was recognized as an expensive undertaking requiring a step-by-step approach to demonstrate its feasibility. The first step to be taken was the setting up of a programme to develop and demonstrate the processing, transmission, and display techniques which are the key to the successful operation of such a network. In the first instance, these techniques were developed for a prototype single-radar configuraton, enabling processed data to be transmitted from the radar site and displayed remotely. This prototype system was demonstrated for the first time in late 1973, and work is now in progress on the extension and implementation of these techniques for network operation. By the end of 1974, it is hoped that there will be a small network linking three or four radar sites. This network will be used primarily for basic meteorological research but also as part of a feasibility study for the possible implementation of an operational Weather Radar Network. In the present paper the authors describe the overall system concept and the kind of data the system will provide. Some of the specific features of the processing, transmission, and display techniques used in the RRE prototype system are also outlined. Since this paper is aimed mainly at meteorologists, hydrologists, and other potential users, we have tried where possible to avoid technical detail and references to technical literature. (Author's summary)

33. Winston, H. A., and Ruthi, L. J. 1986. "Evaluation of RADAP II Severe-Storm-Detection Algorithms," *Bulletin of the American Meteorological Society*, Vol 67, No. 2, pp 145-150.

Computer-generated volumetric radar algorithms have been available at a few operational National Weather Service sites since the mid-1970's under the Digitized Radar Experiment (D/RADEX) and Radar Data Processor (RADAP II) programs. The algorithms were first used extensively for severe-storm warnings at the Oklahoma City National Weather Service Office (WSFO OKC) in 1983. RADAP II performance in operational severe-weather forecasting was evaluated using objectively derived warnings based on computer-generated output. Statistical scores of probability of detection, false-alarm rate, and critical-success index for the objective warnings were found to be significantly higher than the average statistical scores reported for National Weather Service warnings. Even higher

statistical scores were achieved by experienced forecasters using RADAP II in addition to conventional data during the 1983 severe-storm season at WSFO OKC. This investigation lends further support to the suggestion that incorporating improved reflectivity-based algorithms with Doppler into the future Advanced Weather Interactive Processing System for the 1990's (AWIPS-90) or the Next Generation Weather Radar (NEXRAD) system should greatly enhance severe storm detection capabilities. (Author's abstract)

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